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# CPU Cooling Pulse Device for Enhanced Heat Transfer

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## **CPU Cooling Pulse Device for Enhanced Heat Transfer**

April 30, 2019

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\*Submitted in Partial Fulfillment  
of the Requirements for  
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# TABLE OF CONTENTS

<b>Executive Summary</b>	4
<b>Background</b>	7
<b>1. Customer needs</b>	9
1.1 Introduction	9
1.2 Identifying Needs	9
1.3 Voting Process	11
Affinity Diagrams	11
1.4 Explanation of Needs	13
1.5 Problem/Mission Statement	14
<b>2. Project Specifications</b>	15
2.1 Introduction	15
2.2 Introduction of Metrics	15
2.3 Needs Metrics	16
2.4 Target Specifications for Metrics	18
<b>3. Functional Concepts</b>	23
3.1 Introduction	23
3.2 Alternative Solutions to Functional Problems	25
3.3 Introduction of CCT with Selected Combinations	27
Concept Combination I	28
Concept Combination II	30
Concept Combination III	32
Concept Combination IV	34
Concept Combination V	36
3.4 Research/Patent Review	38
<b>4. Concept Selection</b>	39
4.1 Introduction	39
4.2 Selection Criteria	40
4.3 Concept Evaluation	43
AHP's Rating	45
4.4 Final Concepts	51
<b>5. Product Architecture</b>	53
5.1 Introduction	53
5.2 Grouping of Functional Elements	53
5.3 Interaction of Elements	55
5.4 Geometric Component Layout	57
5.5 CAD Model	59

<b>6. Engineering Analysis</b>	65
6.1 Introduction	65
6.2 Analysis Approach	65
6.3 Governing Equations	67
6.4 Outputs	71
6.5 Results	75
<b>7. Manufacturability</b>	76
7.1 Design for X	76
7.1.1 Introduction	76
7.1.2 Design for Manufacturing	77
7.1.3 Design for Cost	79
7.1.4 Design for Environment	80
7.1.5 Design for Ergonomics	83
7.1.6 Design for Durability	83
7.1.7 Design for Assembly	84
7.2 Build Instructions	85
7.2.1 Introduction	85
7.2.2 Fabrication	87
7.2.3 Assembly Instructions	90
<b>8. Product Cost/Economic Analysis</b>	99
8.1 Introduction	99
8.2 Product Value	99
8.3 Associated Costs	100
8.4 Benefits/Savings/Revenues	102
8.5 Suggested Approaches	103
8.6 Summary	106
<b>9. Testing</b>	107
9.1 Introduction	107
9.2 Test Equipment	107
9.3 Testing Process	108
9.4 Test Matrix	109
9.5 CPU Liquid Cooling System Without Pulses	109
9.6 Pulse Device at Varying Frequencies	110
9.7 Pulse Device Efficiency Based on Temperature	110
9.8 Conclusions	111
<b>10. Final design/Conclusions on Designed Product</b>	112
10.1 Summary of Designed Product Results	112
Final Drawings	112

Specifications	115
Bill of Materials	115
10.2 Future Product Development	116
10.3 Lessons Learned	116
<b>Appendices</b>	117
<b>References</b>	119
<b>Acknowledgments</b>	121

## **Executive Summary**

Ice Dragon Cooling is a company which researches thermofluids and heat transfer technologies. The company's present research focuses on HVAC and computer applications, with an emphasis on nanofluid development. To support Ice Dragon's mission, the company wants a product that enhances heat transfer efficiency in liquid-cooled CPU systems. The product is to be a pulse device which increases the turbulence of a liquid across a computer CPU cooling block, thereby expediting heat transfer away from the CPU.

The needs for Ice Dragon Cooling were determined based on engineering knowledge and industry consultation. After further analysis, it was determined that increasing the heat transfer rate, achieving turbulent flow, maintaining net-zero energy, preserving the original system's pump, and ensuring durability were critical to satisfying those needs. Furthermore, it was determined that in order to satisfy the requirements, the pulse device needs to increase flow rate and Reynold's number value, be made of a sturdy and waterproof material, and consume minimal power. It was thus determined that the project mission is to create a CPU liquid-cooling pulse device that will increase heat transfer and efficiency within the system.

Given the above requirements, various concepts were researched and discussed, as detailed in the full report. The final selected concept to best satisfy Ice Dragon's needs was a piston-jet combined concept. Information pertaining to concept selection and product architecture are provided.

A detailed engineering analyses is provided, displaying flow velocity, temperature, and pressure. The analysis also demonstrates how these elements lead to the generation of turbulence and inducement of heat transfer. Under the assumptions that heat in the system is generated from

both the cooling block and the jets and that the flow is homogeneous, incompressible, and laminar, the tested parameters included dissipated heat from the cooling block, pressure drop from the pistons pushing water through the jets, and velocity change at jet inlets and across the microchannels.

The prototype testing process involves three separate tests, with one as a control experiment and two to assess the degree of functionality of the device. By running the original system without the pulse device, a baseline was established against which the data of the new system could be compared. The second test focuses on demonstration of the pulses in relation to the flow through the device. A flowmeter monitored the flow rate for trials of varying inputted frequencies. The third test focuses on the heat transfer rate across the cooling block. Thermocouples placed at the inlet and outlet of the cooling block are used to record the temperature differentials necessary to calculate the heat transfer rate.

Economic analysis of the scope of expenses associated with development of the prototype indicates that, for a \$153.70 investment per presealed system, Ice Dragon Cooling will recover costs within the first month of production. Applications of this device to the server farm industry and individual consumers are suggested viable options for the company.

The Ice Dragon pulse device can be ameliorated in the future, with improvements including more reliable sealing, standardization of fittings, and upgraded piston functionality. Sealing of the pistons and cylinder can be improved to effectively prohibit the presence of water into the piston-cylinder mechanism and to prevent fluid losses from the circulatory system. Tube fittings at the inlets and outlets of the device can be bettered by standardization to ensure CPU cooling market consistency and availability of parts in the future. The current piston function is

too slow to meet the efficiency needs of the product, but all other parts run smoothly. Therefore, the primary change to be made with respect to device functionality is in terms of the removal of resistance by the pistons. Further testing of the design is also recommended to obtain a fuller and more accurate analysis of the results.



## **Background**

### **Ice Dragon Cooling**

Ice Dragon Cooling is a thermal fluid and heat transfer engineering design company started by Dr. Dale McCants and Dr. Andrew Hayes. The idea for the company was developed while they were graduate students at the University of South Carolina. The project they were working on at the time was investigating the heat transfer enhancement potential of nanofluids. The research showed that there was a significant increase in heat transfer using nanofluids in thermal management systems. After completing their PhDs they founded Ice Dragon Cooling. Since the founding of Ice Dragon, the company has invested its research into the development of state-of-the-art nanofluid coolants and creating new technologies to push the boundaries of heat transfer. Currently they are applying their research in the HVAC industry and are looking into other industries where they can apply nanofluid technologies.

### **Project Scope**

For this project a net zero pulse device will be designed to induce turbulence to the laminar microchannel flow of a CPU cooling block. This device will be designed to be an all in one and mount to a supplied CPU cooling block (the copper part). The device will include a net zero pulse pump and the pump and will mount directly to the cooling block with the pulse pump all together. The purpose will be to take an existing microchannel cooling block and mount the final design directly to it for use in a PC. By industry sponsor request, a functioning prototype is the main deliverable of this project.

## **Mission Statement**

The mission of the Ice Dragon Cooling senior design team is to create a CPU liquid cooling pulse device that will increase heat transfer and efficiency within the system.

# **1. Needs**

## **1.1. Introduction**

The Ice Dragon Cooling Senior Design Team consists of Hannah Farabee, Noémie Iniguez, Hugo Nunez, and Wendy Zwanka. The indicated customer for this project is Ice Dragon Cooling, a company started by Dr. Dale McCants. The first meeting was held over a Skype video call on September 20, 2018. This meeting was helpful in determining the scope of the project and identifying the required needs. The main goal of this project was to increase heat transfer by inducing turbulence to the laminar microchannel flow of a CPU cooling block. This was achieved through the design of a net zero pulse device that mounts directly to the cooling block.

## **1.2 Identifying Needs**

With the information gathered, the needs were categorized and defined based on priority. As software and computational advances are made in today's rapidly evolving digital world, a need for higher processing power is crucial. The need for better cooling in more powerful CPUs is required which is performed through a liquid cooled system. After a design meeting, it was determined that the pulse device must meet design specifications, thermodynamic properties, and manufacturing requirements that will optimize efficiency. The specific values were determined following the first meeting with the company.

### ***Design Specifications***

1. Sized to fit in space available
2. Material
3. Low cost
4. Simple design
5. Small amount of parts
6. Durability
7. Holes to determine flow
8. Easy assembly of part into computer
9. Preservation of original pump
10. Remain pre-sealed system
11. Net zero pulse generator
12. Ability to pull fluid in and push fluid out at specific velocity

### ***Thermodynamic Properties***

1. Turbulent flow / High Reynolds number
2. High heat transfer rate to cool CPU
3. High velocity
4. Compatible with CPU mount

### ***Manufacturing***

1. Low manufacturing complexity
2. Ability to be 3D printed / machined

### 1.3 Voting Process

The voting process was undertaken via a Google Spreadsheet. Each member was assigned a sheet with the listed needs in one column and an empty column for rank assignment. In Round 1, each voter analyzed the full list of needs and made a personally-opinionated ranking of the needs in descending order of rank from 1 to 6. The needs were then re-evaluated to only include the top 5 agreed-upon needs and the voting process was repeated for Round 2 with the top 5 agreed-upon choices. This method resulted in the top 3 needs being determined via discussion. Rounds 1 and 2 are shown in the Affinity Diagrams below which detail each member's votes.

### Affinity Diagrams

Table 1. Round 1 of Affinity Diagram

Round 1						
Need	HF	NI	HN	WZ	Total	Rank
Size						
Material						
Fit in space available						
Low cost	5		6	4	15	6
Simple design						
Small amount of parts						
Durability		5	4	5	14	5

Holes to determine flow						
Easy assembly						
Preservation of original pump	4	4		6	14	4
Remain pre-sealed system						
Net zero energy	2	3	2	3	10	3
Ability to suck fluid in and push fluid out						
Turbulent flow / High Reynolds number	3	2	3	2	10	2
High heat transfer rate	1	1	1	1	4	1
Cool CPU						
High velocity						
Compatible with CPU mount	6	6	5		17	7
Low manufacturing complexity						
Ability to be 3D printed / machined						

Table 2. Round 2 of Affinity Diagram

<b>Round 2</b>						
<b>Need</b>	HF	NI	HN	WZ	Total	Rank
Durability	5	5	5	4	19	5
Preservation of original pump	4	4	4	5	17	4
Net zero energy	3	3	3	3	12	3
Turbulent flow / High Reynolds number	2	2	2	2	8	2
High heat transfer rate	1	1	1	1	4	1

#### **1.4 Explanation of Needs**

After evaluating the Affinity Diagrams for the needs, it was evident that the primary needs were: high heat transfer rate, turbulent flow, and net zero energy. All other needs previously listed were still relevant, but were secondary needs. The primary needs are described as follows:

##### ***High Heat Transfer Rate***

The most important need for this project was to increase the heat transfer between the fluid and the cooling block by creating turbulent flow. The higher the heat transfer, the higher the efficiency of the cooling system.

### ***Turbulent Flow***

The generation of turbulent flow is a known method to increase heat transfer. Turbulent flow causes a sporadic motion of particles and in turn allows a high heat transfer coefficient, ultimately resulting in a high heat transfer rate. Turbulent flow was therefore needed to maximize efficiency in the cooling system.

### ***Net Zero Energy***

It was imperative to have a net zero energy, or equal amount of energy entering and leaving the cooling system. Upholding this balance assured that the energy rate of the cooling system did not affect the surrounding parts of the computer.

## **1.5 Problem/Mission Statement**

Ice Dragon Cooling needs a net zero CPU liquid cooling pulse device that increases heat transfer and efficiency within the system.



## **2. Product Specifications**

### **2.1. Introduction of Chapter**

After establishing the primary and secondary needs of the Ice Dragon Cooling project, it was necessary to establish product specifications. Product specifications comprise of the quantitative statement that a project hopes to achieve. Each customer need was formulated into a metric, a measurable quantity, and paired with the appropriate unit of measurement. Importance level of the needs was then rated and used to establish ideal and marginally acceptable target specifications for the design. This process is essential for the Ice Dragon Cooling project to satisfy as many customer needs as possible.

### **2.2. Introduction of Metrics**

Based on the customer needs outlined in Chapter 1, the following metrics were established. Metrics are dependent variables, meaning they are objective, measurable, and have been paired with corresponding units as shown in Table 2.1.

Table 2.1 Product Metrics

<b>Need</b>	<b>Metrics</b>	<b>Units</b>
Fit in space available	Shape	mm <sup>3</sup>
Low cost	Price	\$
Ease of manufacturing	Production Time	Seconds
Ability to pull in and push out fluid	Pump Power	Watts
Turbulent flow	Reynold's Number	Unitless
High heat transfer rate	Efficiency	%
Low noise	Noise	Decibels
Operate at varying frequencies	Frequency	Hz
Durable	Life	Days

### **2.3. Needs Metrics Matrix**

In order to create the Needs Metrics Matrix, all of the customer requirements were paired with a metric used to measure the requirement. Each metric was assigned a unit. The customer requirements were then given a ranking of 1 (lowest) to 10 (highest) on the importance weight factor, i.e. how important they are to the project. After the customer requirements were ranked, each metric was analyzed against each customer need. For each metric-need pair, a score of 0-10 was given to each need based on how much the need related to the metric. After all metrics and needs were analyzed together, a raw score was assigned to each metric by summing the products

of the score from the metric by the importance weight factors of the corresponding needs. This method was performed for each metric. The relative weight was then established by dividing the raw score by the sum of the scores for each metric, then multiplying by 100. The relative weights were then used to rank the order of the needs in order from the most (1) to the least (14) important metric. The result of the metrics matrix is shown in Table 2.2.

**Table 2.2 Needs-Metrics Matrix**

		Engineering Characteristics													
Improvement Direction		↓	↓	↑	↑	↓	↓	↑	↓	↑	↓	↓	↓	↓	↑
Units		\$	#	Unitless	°C	Decibels	Watts	mm^3	Days	sec	mm^3/	rpm		Watts	%
Customer Requirements	Importance Weight Factor	Cost	Number of Parts	Reynold's Number	Heat Resistance	Noise	Power consumption	Shape	Durability	Ease of Manufacturing	Flow Rate	Motor Rotation	Ease of Product Use	Pump Power	Efficiency
Material	3	9			9				9	5					
Fit in space available	8		3					9		7			7		
Low cost	6	9								9					
Simple design	4	5	7					5	5	9			9		
Small amount of parts	4	5	9							7			7		
Holes to determine flow	2							9			9				5
Preservation of original pump	8						9			7		9		9	
Remain pre-sealed system	10	7				5			3			7	9	5	
Net zero pulse generator	10			9		9	9	3			9	5		7	9
Ability to pull fluid in and push out	10							9			9	5		9	9
Turbulent flow	10			9				9			9			5	9
High heat transfer rate	10			9	5						9			7	9
Cool CPU	10			9	9		9	9	7		9	3		3	9
Low Noise	5					9						7		5	
<b>Raw Score</b>		196	304	1,440	529	575	756	2,862	648	1,452	2,808	1,908	832	3,650	2,600
<b>Relative Weight (%)</b>		560	1,600	4,000	2,300	2,500	2,800	5,400	2,700	3,300	5,200	5,300	2,600	7,300	5,200
<b>Rank Order</b>		14	13	6	12	11	8	2	9	7	4	3	10	1	5

Table 2.2 was used to establish the order of importance of the metrics. Based on Table 2.2, the most important metric was Pump Power as it directly affected over half of the customer

needs, including the top three needs (turbulent flow, high heat transfer rate, and to cool the CPU). The reason the pump power affected these is because the focus of the project was to use a pulse device to increase heat transfer while decreasing the input energy, so using the same pump and pump power was vital to this process. The second most important metric was the shape of the pulse device since the shape of the design directly relates to the flow turbulence, which was the main need of this project. The shape of the device determined if it fit in the space available and the flow's potential to become turbulent. The third most important metric was the motor rotation since the pulse device needed to be run at the same motor rotation as the pump in order to stay synched with the system and use minimal energy. The top three metrics were the main focuses for the project going forward.

#### **2.4. Target Specifications for Metrics**

After the derivation of metrics from needs, specific values for the quantifiable needs were developed. These specific values comprised of the target specifications and their fallback values. Target specifications describe the values for certain needs which yield the best results with respect to the described needs. The fallback values describe the next-best possible results which are the acceptable values that do not show a reversal of progress in the machine. Considering the most relevant needs and research of related studies, approximations for these values were selected.

The key equations for this design project are largely related to fluid movement and heat transfer. These include:

$$Q = h \cdot A \cdot \Delta T \quad \text{Eq. 1}$$

Equation 1 is the Heat Loss Equation. Q is the rate of heat loss across a surface area A, h is the convective heat coefficient of the fluid passing across the area, and  $\Delta T$  is the temperature difference at each end of the area.

$$\frac{\delta}{\delta x}(k \frac{\delta T}{\delta x}) + \frac{\delta}{\delta y}(k \frac{\delta T}{\delta y}) + \frac{\delta}{\delta z}(k \frac{\delta T}{\delta z}) + q_{dot} = 0 \quad \text{Eq. 2}$$

Equation 2 is the Heat Diffusion Equation. This gives the temperature distribution which represents how temperature varies with position within a medium. T is the temperature, k is the thermal conductivity of the material,  $q_{dot}$  is the rate at which energy is generated per unit volume of the medium (unit volume expressed using x, y, and z cartesian coordinates).

$$P_1 + \frac{1}{2} \cdot \rho \cdot V_1^2 + \rho \cdot g \cdot h_1 = P_2 + \frac{1}{2} \cdot \rho \cdot V_2^2 + \rho \cdot g \cdot h_2 \quad \text{Eq. 3}$$

Equation 3 is Bernoulli's Equation for incompressible fluid flow (for any point along a streamline). The left side of the equation represents the channel inlet and the right side of the equation represents the channel outlet. On both sides of the equation: P is the pressure,  $\rho$  is the fluid density, V is the fluid velocity, g is the gravitational acceleration constant, and h is the change in height.

$$Re = \frac{\rho \cdot V \cdot L}{\mu} \quad \text{Eq. 4}$$

Equation 4 is for the Reynolds Number, where  $\rho$  is the fluid density,  $V$  is the fluid velocity,  $L$  is the length of the channel being considered, and  $\mu$  is the kinematic viscosity of the fluid. The Reynolds Number is an expression of the ratio between the inertial force and the viscous force of a fluid through a channel of specified length. The magnitude of the resulting number is indicative of the flow regime. For  $Re < 2000$ , the flow is laminar; for  $2000 < Re < 4000$ , the flow is transient, and for  $Re > 4000$ , the flow is turbulent.

$$\frac{1}{U \cdot A} = \Sigma \frac{1}{h \cdot A} + \Sigma R \quad \text{Eq. 5}$$

Equation 5 is The Overall Heat Transfer Coefficient (U) Equation.  $A$  is the surface area being subjected to heat transfer,  $h$  is the convective heat transfer coefficient of the fluid being subjected to heat transfer due to convection, and  $R$  is the resistances to heat flow within the channel wall.

$$Q = m \cdot C_p \cdot \Delta T \quad \text{Eq. 6}$$

Equation 6 is the Heat Rate Equation.  $m$  is the mass flow rate,  $C_p$  is the specific heat capacity of the fluid being subjected to heat transfer, and  $\Delta T$  is the temperature difference between the inlet and the outlet of the channels.

Table 2.3. Target Specifications

<b>Metrics</b>	<b>Target</b>	<b>Fallback</b>
Material	ABS	PLA
Shape	50 - 100 mm	120 mm
Cost	\$150	\$200
Ease of Manufacturing	3D Printing	Machining
Flow Rate	120 L/h	100 L/h
Radiator Fan Speed	500-2160 rpm	2400 rpm
Power consumption	30% decrease	20% decrease
Pump Speed	2565 - 2619 rpm	2850 - 2910 rpm
Reynold's Number	5000	4000
Heat Resistance	>116°C	N/A

Table 2.3 includes target and fallback specifications for the identified metrics. 3D printing of the device allows for flexibility in the design and in manufacturing of the product which were useful for the prototyping stage. ABS was a good choice of material for this design due to its high heat resistance, strength, flexibility, and durability. Its heat resistance of up to 116°C was sufficient as the Intel core series and AMD Ryzen series of CPUs have maximum listed temperatures of 95 and 100°C. Using an efficient material like ABS and preserving the old pump was critical in maintaining a lower cost. With the many variants and factors that go into

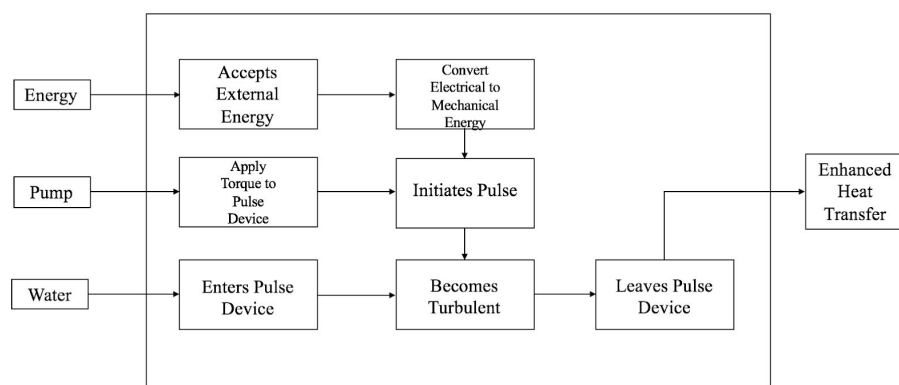
liquid cooled systems, the EVGA CLC 240 Liquid CPU Cooler was used as a reference. Based on the specifications researched, the target cost was \$5-20 for the pulse device added on to the presealed liquid cooled system (90\$) with a fallback of \$30. The design of the pulse device was to be constrained to 50-100 mm with a maximum height of 120mm so that the components stay within the chassis and so that it is not oversized. With a target efficiency increase of 10%, the noise level, power consumption, and pump power will go down resulting in less energy consumption. The estimated installation time was found to be 2-5 minutes with a maximum of 10 minutes to complete for the customer. The final product was based on the customer needs, their metrics, and target specifications. The main goal was to attain all of the target specifications. Fallback values were used if necessary depending on certain aspects of the design in order to be successful in achieving the best quality design and product.



### 3. Functional Concepts

#### 3.1. Introduction of Chapter

After defining the needs and the product specifications, the next step in the design process was to determine the functional concepts. Functional decomposition is the process of identifying the different interactions between the parts, energy, signals, and breaking it down into small and simple tasks. This process helps to foster smooth and easy build and ensures that all concepts are accounted for in the total solution, while keeping function solutions neutral. Each individual element of the process and their hierarchical relationship to each other are displayed in a functional decomposition diagram. This diagram considers only “what” the product needs to accomplish through its lifespan without specifying “how” it achieves its desired goal. These “whats” are usually separated into categories such as material, energy, and signal, which then are used to reach a final goal. The functional diagram for this product is shown in Figure 1, with a final goal of enhanced heat transfer.



**Figure 3.1.** Functional decomposition diagram

Figure 1 illustrates the steps the mechanism needs to achieve to accomplish enhanced heat transfer. The specifics of each step are detailed below:

- **Accepts external energy:** For the majority of concepts defined in this chapter, energy input was required for the operation. This energy can vary in type greatly.
- **Convert electrical to mechanical energy:** A liquid cooling system involves electrical energy produced by the impeller of the pump. Using the impeller allows for the frequency to be constant throughout the device. Electrical energy becomes mechanical so that the pulse can be initiated.
- **Apply torque to pulse device:** The pump provides a turning force, or torque, to the pulse device to produce rotational motion in the system.
- **Initiates pulse:** This function defines how the water will be pulsed, and then attained by some method of pressure or vibration.
- **Enters pulse device:** The device begins the process by water entering the pulse device which will be achieved in a variety of different ways.
- **Becomes turbulent:** This function is unique to each individual concept. Due to the design parameters, there are multiple ways to induce turbulence within the pulse device and disturb or alter the system flow.
- **Leaves pulse device:** Once the water goes through the change in flow, it must leave the device to enter the cooling block. This can be achieved by a simple push, pull, etc.

### 3.2. Alternative Solutions to Functional Problems

After all of the functional elements were determined for the system, they were analyzed by identifying all of the different ways each functional element could be accomplished. To determine all of the ways each element was to be accomplished, research was conducted on the current cooling systems available, and brainstorming helped to come up with new ways to accomplish these elements. The following table (Figure 2) displays all of the “how’s” to correspond with all of the “what’s” of the system.

Accepts External Energy	Convert Electrical to Mechanical Energy	Apply Torque to Pulse Device	Initiates Pulse	Enters Pulse Device	Becomes Turbulent	Leaves Pulse Device
Electrical	DC Electric Motor	Force Generated by Impeller	Spring	Pulled	Velocity	Pulled
Battery	Electro-magnetic	DC Electric Current	Pneumatic	Pushed	Pressure	Pushed
Pneumatic	Angular Kinetic Energy	Human Input	Pistons	Vacuum	Shape of Shaft	Vacuum
Actuator		Shaft Connected to Impeller	Turbine			
Hydraulic			Water Wheel			
			Discrete Vibration			
			Rotational Discrete Vibration			
			Jets			

**Figure 3.2.** Concept Combination Table

The Concept Combination Table was created by breaking down the flows of the energy, pulse, and water throughout the system. The broken up tables are shown in Figures 3, 4, and 5.

Energy	
Accepts External Energy	Convert Electrical to Mechanical Energy
Electrical	DC Electric Motor
Battery	Electro-magnetic
Pneumatic	Angular Kinetic Energy
Actuator	
Hydraulic	

Pulse	
Apply Torque to Pulse Device	Initiates Pulse
Force Generated by Impeller	Spring
DC Electric Current	Pneumatic
Human Input	Piston
Shaft Connected to Impeller	Turbine
	Water Wheel
	Discrete Vibration
	Rotational Discrete Vibration
	Jets

Water		
Enters Pulse Device	Becomes Turbulent	Leaves Pulse Device
Pulled	Velocity	Pulled
Pushed	Pressure	Pushed
Vacuum	Shape of Shaft	Vacuum

**Figure 3.3** Energy Flow

**Figure 3.4** Pulse Flow

**Figure 3.5** Material Flow

### **3.3. Introduction of CCT with Selected Combinations**

Based on the Concept Combination Table, five combinations were selected for possible designs of the pre-sealed cooling system. These all were initiated by an actuator which accepts an energy input and converts electrical energy to mechanical energy. Two concepts employ the manipulation of fluid velocity based on current research by Dr. Guiren Wang, which, if used, will be an application of a new concept in fluid mechanic engineering. In all conceptual cases, the pulse generator is an original design in and of itself. The other primary option (for which there are two concepts) employs the use of a shaft with impeller within the pulse device. This is a flexible approach, since the shape of the impeller alone can be manipulated to give varied flow characteristics. The outlying concept involves the use of resultant pressure differences from a pneumatic system built into the pulse device.

The five concept combinations are described below, including a verbal description of the conceptual design, and a sketch of a possible approach to the concept combination.

## Concept Combination I

Energy	
Accepts External Energy	Convert Electrical to Mechanical Energy
Electrical	DC Electric Motor
Battery	Electromagnetic
Pneumatic	Angular Kinetic Energy
Actuator	
Hydraulic	

**Figure 3.3a**

Pulse	
Apply Torque to Pulse Device	Initiates Pulse
Force Generated by Impeller	Spring
DC Electric Current	Pneumatic
Human Input	Piston
Shaft Connected to Impeller	Turbine
	Water Wheel
	Discrete Vibration
	Rotational Discrete Vibration
	Jets

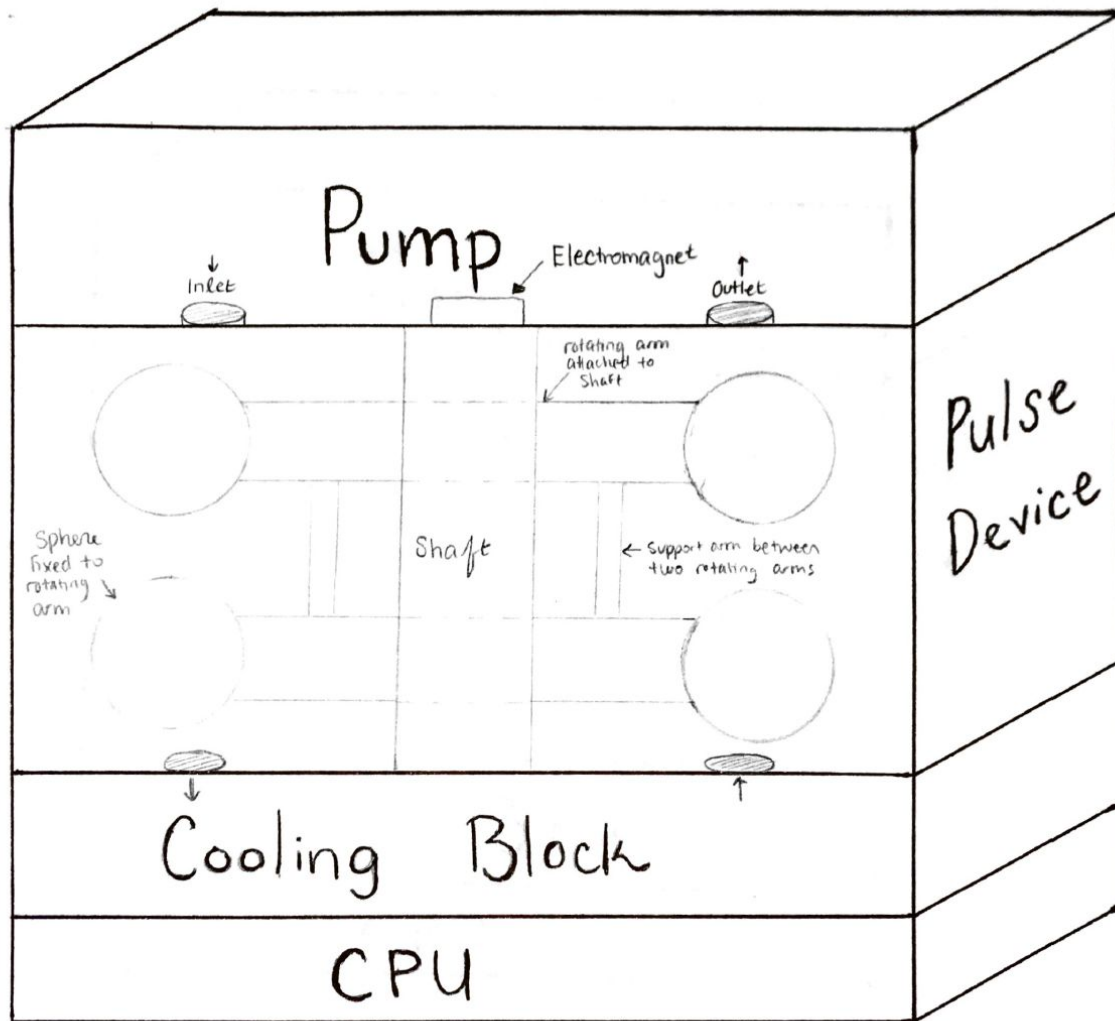
**Figure 3.4a**

Water		
Enters Pulse Device	Becomes Turbulent	Leaves Pulse Device
Pulled	Velocity	Pulled
Pushed	Pressure	Pushed
Vacuum	Shape of Shaft	Vacuum

**Figure 3.5a**

As shown in Figures 3a, 4a, and 5a above, water is rotated in the pump, passing over the inlet and outlet holes in the floor of the pump. An electromagnet on the rotating body of the pump serves as the actuator for this system, and the electrical energy of the pump is converted to mechanical energy by electromagnetism. The rotating body of the pump is connected to a shaft with an impeller in the pulse device. This connection applies torque to the pulse device. The torque applied to the shaft drives the impeller and causes rotational discrete vibration, initiating a pulse. The shape of the impeller characterizes the pulse. The pulse causes the water rotating

within the pump to be pulled in through a hole, become turbulent, and be pushed out through a hole to the cooling block. Figure 6 shows the concept visually.



**Figure 3.6.** Concept Combination I

## Concept Combination II

Energy	
Accepts External Energy	Convert Electrical to Mechanical Energy
Electrical	DC Electric Motor
Battery	Electromagnetic
Pneumatic	Angular Kinetic Energy
Actuator	
Hydraulic	

**Figure 3.3b**

Pulse	
Apply Torque to Pulse Device	Initiates Pulse
Force Generated by Impeller	Spring
DC Electric Current	Pneumatic
Human Input	Piston
Shaft Connected to Impeller	Turbine
	Water Wheel
	Discrete Vibration
	Rotational Discrete Vibration
	Jets

**Figure 3.4b**

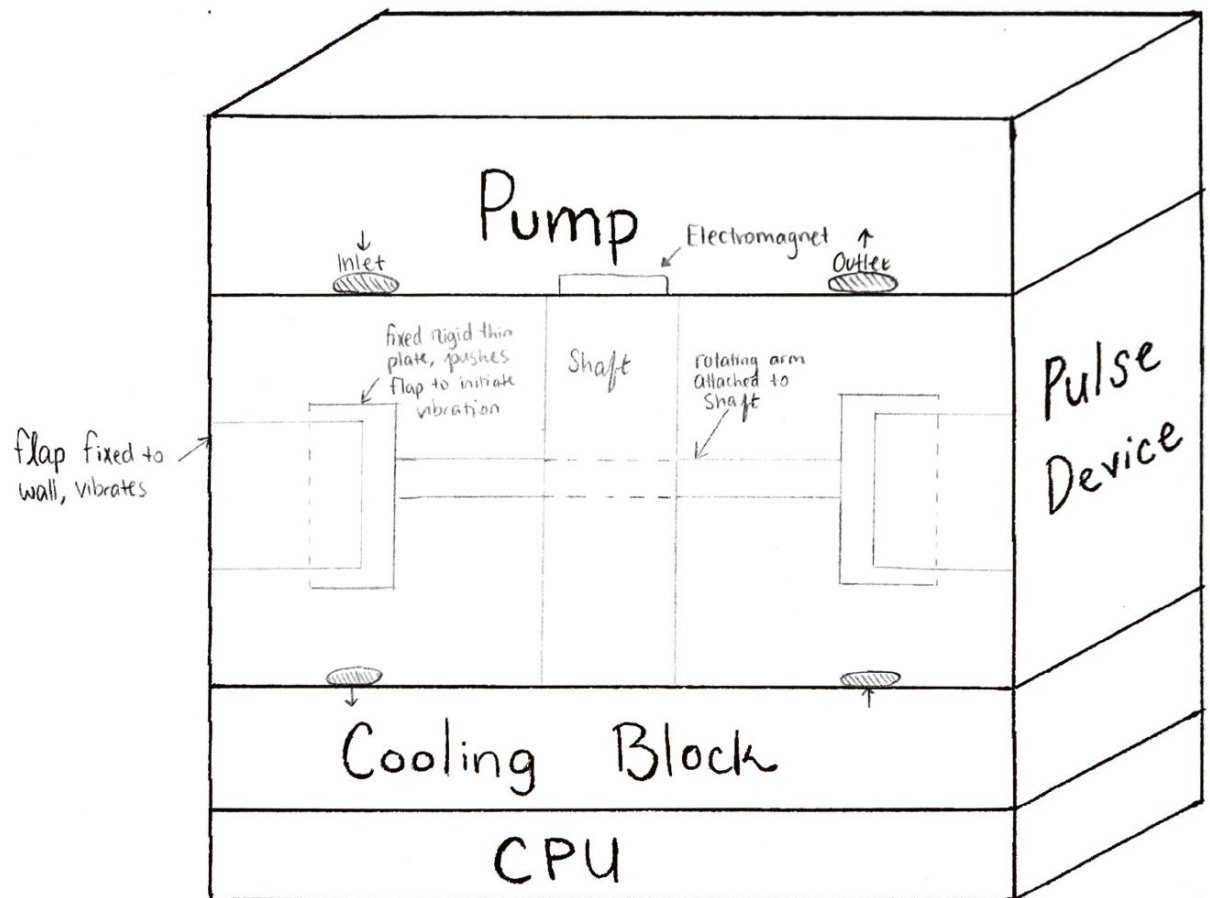
Water		
Enters Pulse Device	Becomes Turbulent	Leaves Pulse Device
Pulled	Velocity	Pulled
Pushed	Pressure	Pushed
Vacuum	Shape of Shaft	Vacuum

**Figure 3.5b**

As shown in Figures 3b, 4b, and 5b above, water is rotated around in the pump, passing over the inlet and outlet holes in the floor of the pump. An electromagnet on the rotating body of the pump serves as the actuator for this system, and the electrical energy of the pump is converted to mechanical energy by electromagnetism. The rotating body of the pump is connected to a shaft with an impeller within the pulse device. This connection applies torque to the pulse device. The torque applied to the shaft drives the impeller and causes discrete vibration, initiating a pulse. The shape of the impeller characterizes the pulse. The pulse causes the water



rotating within the pump to be pulled in through a hole, become turbulent, and be pushed out through a hole to the cooling block. Figure 7 shows this concept visually.



**Figure 3.7.** Concept Combination II

### Concept Combination III

Energy	
Accepts External Energy	Convert Electrical to Mechanical Energy
Electrical	DC Electric Motor
Battery	Electromagnetic
Pneumatic	Angular Kinetic Energy
Actuator	
Hydraulic	

**Figure 3.3c**

Pulse	
Apply Torque to Pulse Device	Initiates Pulse
Force Generated by Impeller	Spring
DC Electric Current	Pneumatic
Human Input	Piston
Shaft Connected to Impeller	Turbine
	Water Wheel
	Discrete Vibration
	Rotational Discrete Vibration
	Jets

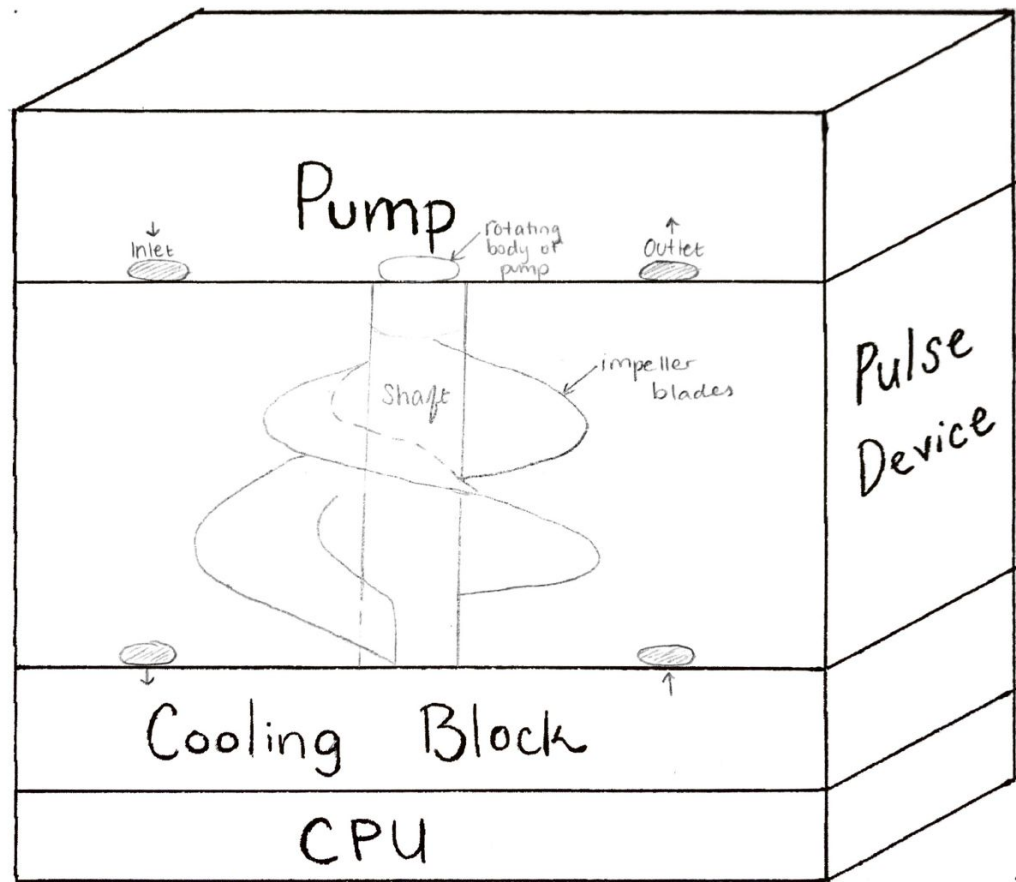
**Figure 3.4c**

Water		
Enters Pulse Device	Becomes Turbulent	Leaves Pulse Device
Pulled	Velocity	Pulled
Pushed	Pressure	Pushed
Vacuum	Shape of Shaft	Vacuum

**Figure 3.5c**

As shown in Figures 3c, 4c, and 5c above, water rotates around in the pump, passing over the inlet and outlet holes in the floor of the pump. The rotating body of the pump serves as the actuator for this system by taking advantage of its own angular kinetic energy to convert the pump's electrical energy to mechanical energy. The rotating body of the pump is connected to a shaft with an impeller in the pulse device. This connection applies torque to the pulse device. The torque applied to the shaft drives the impeller and causes rotational discrete vibration, initiating a pulse. The pulse increases the water velocity to result in a high Reynolds number. The pulse causes the water rotating within the pump to be pulled in through a hole, become

turbulent, and be pushed out through a hole to the cooling block. Figure 8 shows this concept visually.



**Figure 3.8.** Concept Combination III

### Concept Combination IV

Energy	
Accepts External Energy	Convert Electrical to Mechanical Energy
Electrical	DC Electric Motor
Battery	Electromagnetic
Pneumatic	Angular Kinetic Energy
Actuator	
Hydraulic	

**Figure 3.3d**

Pulse	
Apply Torque to Pulse Device	Initiates Pulse
Force Generated by Impeller	Spring
DC Electric Current	Pneumatic
Human Input	Piston
Shaft Connected to Impeller	Turbine
	Water Wheel
	Discrete Vibration
	Rotational Discrete Vibration
	Jets

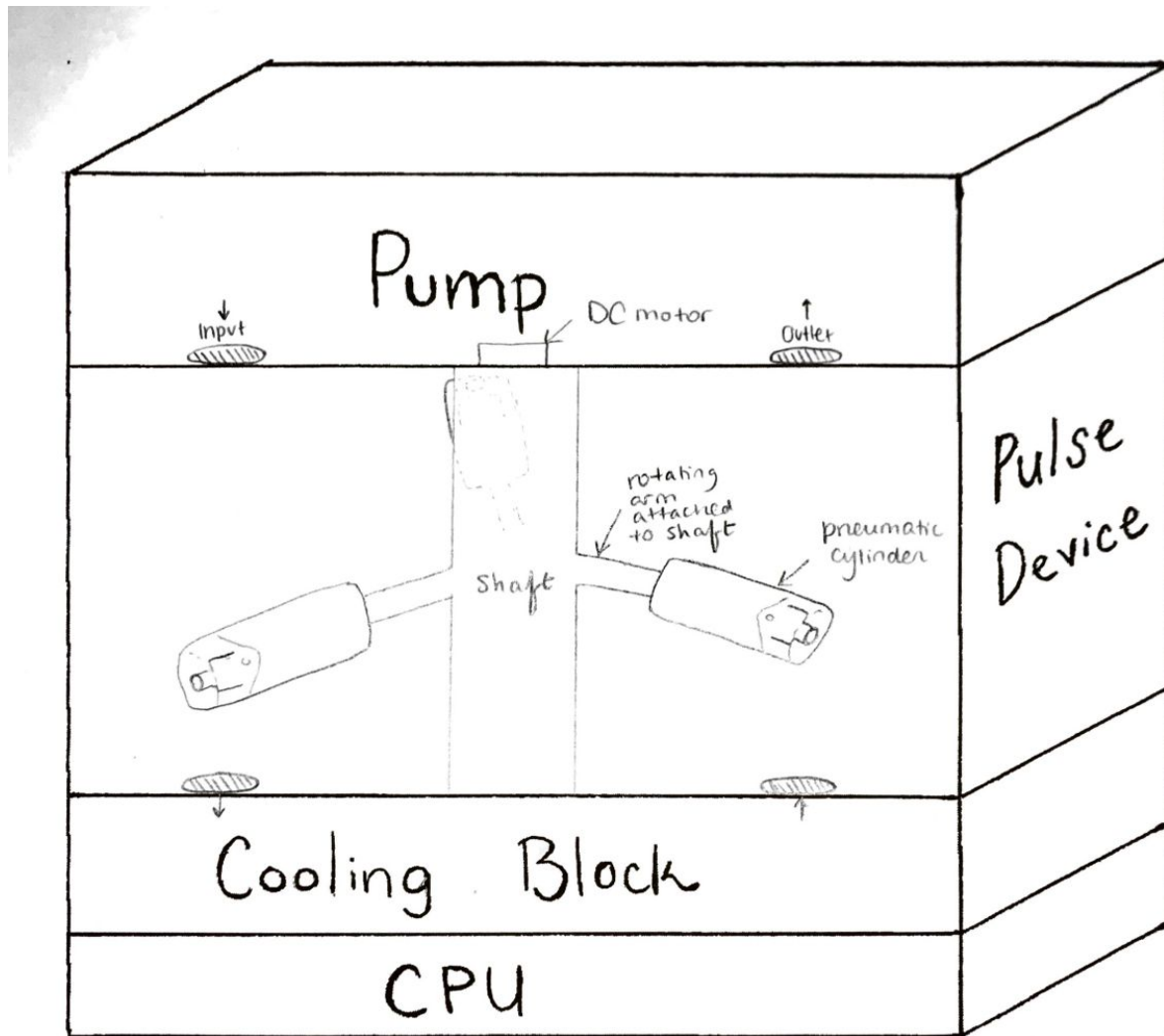
**Figure 3.4d**

Water		
Enters Pulse Device	Becomes Turbulent	Leaves Pulse Device
Pulled	Velocity	Pulled
Pushed	Pressure	Pushed
Vacuum	Shape of Shaft	Vacuum

**Figure 3.5d**

As shown in Figures 3d, 4d, and 5d above, water is rotated around in the pump, passing over the inlet and outlet holes in the floor of the pump. A DC motor on the rotating body of the pump serves as the actuator for this system, and converts the electrical energy of the pump to mechanical energy. The rotating body of the pump is connected to a shaft with an impeller within the pulse device. This connection applies torque to the pulse device. The torque applied to the shaft drives an inner pneumatic system which initiates a pulse. The variable pressure of the pneumatic system characterizes the pulse. The pulse causes the water rotating within the pump to

be pulled in through a hole, become turbulent, and be pushed out through a hole to the cooling block. Figure 9 shows this concept visually.



**Figure 3.9.** Concept Combination IV

### Concept Combination *V*

Energy	
Accepts External Energy	Convert Electrical to Mechanical Energy
Electrical	DC Electric Motor
Battery	Electromagnetic
Pneumatic	Angular Kinetic Energy
Actuator	
Hydraulic	

**Figure 3.3e**

Pulse	
Apply Torque to Pulse Device	Initiates Pulse
Force Generated by Impeller	Spring
DC Electric Current	Pneumatic
Human Input	Piston
Shaft Connected to Impeller	Turbine
	Water Wheel
	Discrete Vibration
	Rotational Discrete Vibration
	Jets

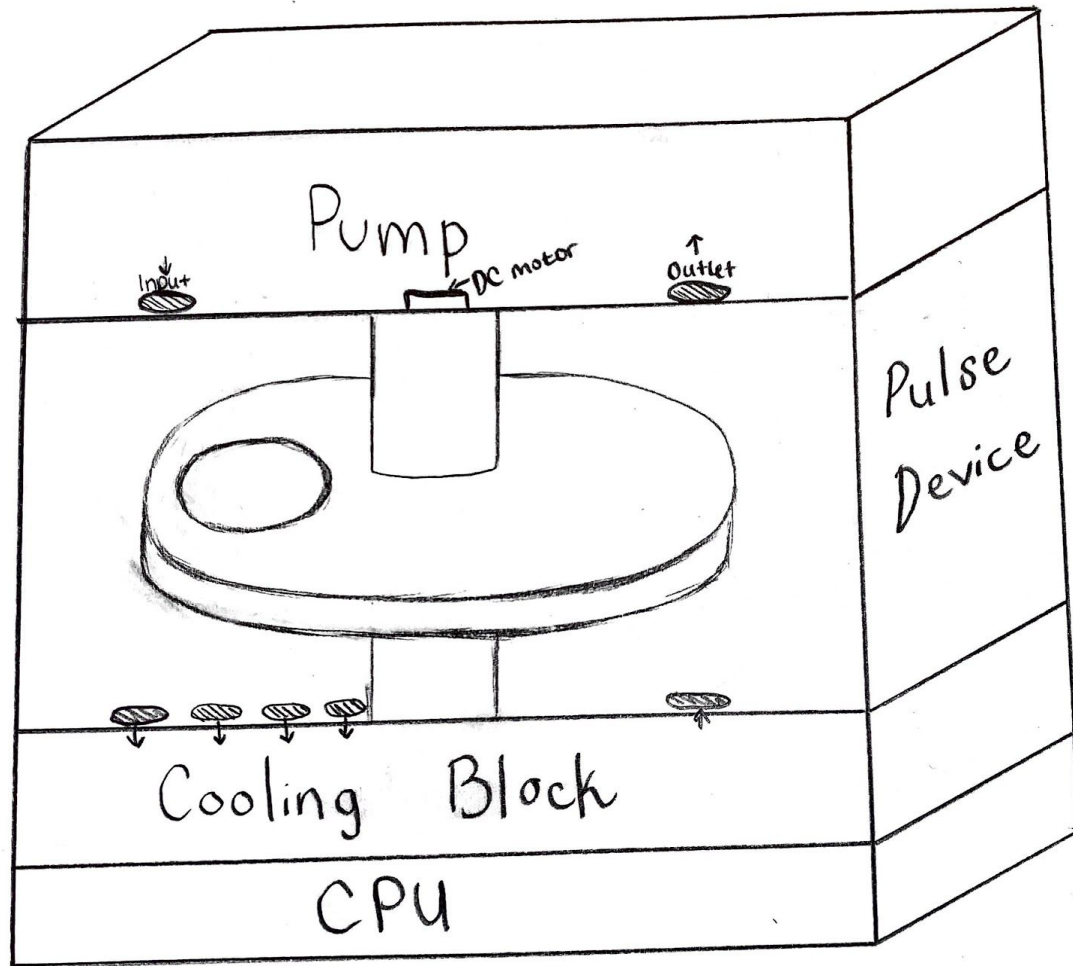
**Figure 3.4e**

Water		
Enters Pulse Device	Becomes Turbulent	Leaves Pulse Device
Pulled	Velocity	Pulled
Pushed	Pressure	Pushed
Vacuum	Shape of Shaft	Vacuum

**Figure 3.5e**

As shown in Figures 3e, 4e, and 5e above, water is rotated around in the pump, passing over the inlet and outlet holes in the floor of the pump. A DC motor on the rotating body of the pump serves as the actuator for this system, and converts the electrical energy of the pump to mechanical energy. The rotating body of the pump is connected to a shaft with an impeller within the pulse device. The impeller applies rotational motion to pistons, initiating a pulse onto synthetic jets. The pulse increases the velocity of the water to result in an appropriately high Reynolds number. The pulse causes the water rotating within the pump to be pulled in through a

hole, become turbulent, and be pushed out through a hole to the cooling block. Figure 10 shows this concept visually.



**Figure 3.10.** *Concept Combination V*

### **3.4. Research/Patent Review**

For the liquid cooling system, it was decided that a pre-sealed system was to be used to produce better results with more control. Pre-sealed systems already have the measurement readings and power functions installed, such as CPU temperature reading and fan and pump speed settings. The components of the system consists of a cooling block, pump, radiator, fan, and tubing. The pulse device will be added to be on top of the cooling block, between the pump. According to research, the proposed pulse device is not on the market or in development with known patents. Cooling blocks are all designed with different microchannel configurations. Cooling blocks are made from copper as it has high thermal conductivity and is good at increasing heat transfer. The selection of the pre-sealed system that will be used must still be determined. A method for enhancing heat transfer is through synthetic jets. These synthetic jets have a zero-net mass flux and induce turbulence while maintaining a low pressure drop. They are formed from the working fluid of the flow system in which they are deployed and can transfer linear momentum without net mass injection across the flow boundary. The jets can be activated by an actuator and can control and modify the flow fields in the microchannels for better heat transfer performance. The synthetic jets can be produced over a broad range of lengths and timescales which allow it to operate under different frequencies.



## **4. Concept Selection**

### **4.1. Introduction of Chapter**

The concept selection chapter takes the functional decomposition chapter and examines its finer points to guide the determination of a final design concept. The selection criteria are decided based on the desired functions of the product, and are a result of revision of the customer needs. These are used to clarify the most important needed aspects of the final design.

The selection criteria were ranked to determine the most viable final design concepts. The concepts were evaluated and underwent a voting process based on the selection criteria in which the top 3 concept designs were kept. The selection criteria were given a rating guideline by the Analytic Hierarchy Process in which weights were obtained for the final rankings. The rating guidelines were used to narrow down the top three concepts by comparison. The selection criteria were compared against one another in the Criteria Comparison Matrix based on importance and were used to form the criteria weights. Based on the weights, the concepts were rated and the top two designs were selected.

## 4.2. Selection Criteria

Table 4.1. Selection Criteria

Selection Criteria
Fit in Space Available
Low Cost
Easy to Manufacture
Ability to Pull in and Push Out Fluid
Turbulent Flow
Increase Heat Transfer Rate
Low Noise
Operate at Varying Frequencies
Durable

The selection criteria were stemmed from a revised analysis of the initially-determined needs. The revision was based on team discussions and advice from the project sponsor. The original list of needs included slightly extraneous elements which were removed in the revision. The selection criteria were important to consider in the product design process because the conceptual designs were completely dependent on them. The ranked and weighted selection criteria paired with the concept drawings were what mathematically determined the final conceptual design. The selection criteria are listed in Table 1 above.

- **Fit in space available**

It is important for the pulse generator to be shaped and sized so as to fit in the specified space because the insides of a computer system unit nowadays are made to be as compact as possible. Additionally, the pulse generator forms part of a pre-sealed system, so its size

must also consider the pre-sealed system. This means accounting for the size and shape of the pump and cooling block once they have been selected.

- **Low cost**

It is beneficial to minimize cost of the design of the pulse generator in order to make the product accessible to more people. Low cost of production allows for easier financial access to materials and fabrication resources, and greater profit from the final product.

- **Easy to manufacture**

Ease of manufacture relates to the cost of materials and production, because easier manufacturing will result in a lower overall cost. A product which is easy to manufacture also provides more varied options for manufacturers, as opposed to a complex design which can only be generated by a few select manufacturers which may not be of the desired quality.

- **Ability to pull in and push out fluid**

The pulse generator must pull fluid into it and push fluid out of it through orifices in order to apply the pulse to the fluid. The pull and push of fluid is the first step to the conversion of flow from laminar to turbulent, therefore the device cannot rely solely on gravity or the movement of the pump to transfer the fluid between the pump and the cooling block.

- **Turbulent flow**

Turbulent flow is the key to heat transfer enhancement, because in this flow regime heat transfer occurs at the walls of the channel. The agitated flow does not develop a steady insulating blanket and therefore heat transfers very quickly. Turbulent flow is achieved

by increasing the velocity of flow adequately. Turbulence can slow the buildup of precipitates on the inside walls of the channel, but a velocity that is too high can cause erosion of the channel. Therefore it is best to just reach the threshold of turbulence, or Reynolds Number  $> 4000$ .

- **Increase heat transfer rate**

The overall goal of this design project is to cool down a CPU, which is primarily and directly connected to the increase of the convective heat transfer rate away from said CPU. An increase in the heat transfer rate is defined as a positively-valued increase in the temperature difference between the fluid entering the cooling block and the fluid exiting the cooling block (which is in direct contact with the CPU).

- **Low noise**

Dry air cooling is known to be a noisy cooling method; liquid cooling is comparatively much quieter. Low noise is a known benefit for customers who choose liquid cooling systems, therefore it is important to preserve this feature as best as possible when designing the additional pulse generator component.

- **Operate at varying frequencies**

The cooling system must be flexible in terms of power—it can accommodate most systems and transfer heat for different frequencies transmitted from the pump signal. Adaptability to a wide range of frequencies allows for consistent cooling within one computer unit regardless of the stress placed upon the system.

- **Durable**

The pulse generator will be incorporated into a pre-sealed system. It is important that the pulse generator be durable, because the primary purpose of the pre-sealed system is ease of installation for the consumer. Therefore, the pulse generator lasts as long as any other component in the pre-sealed system (pump, orifices/channels, cooling block). Replacement of the pre-sealed system is only as frequent as existing systems, or less frequent.

#### **4.3. Concept Evaluation**

After the selection matrix was established, the concepts from the Function Concepts chapter were evaluated and voted upon. A multi-step process was followed to select concepts for the pulse device. The multi-step process included: a concept screening matrix, criteria comparison matrix, normalized criteria comparison matrix, and a final concept scoring matrix. The concepts voted on include the five concepts from the functional concepts chapter. For scoring, “0” represents a neutral standing, a “-” is of less importance and a “+” represents a better standing when compared to the selected reference point. The “reference” concepts is based off a standard CPU Liquid Cooling Unit that is currently on the market without an added pulse device. Choosing this reference facilitated determination of the concept with the most advantages to a baseline liquid cooling unit. Table 2 shows the Concept Screening Matrix.

Table 4.2. Concept Screening Matrix

Selection Criteria	Concepts					
	Reference	1	2	3	4	5
Fit in space available	0	+	0	-	-	+
Low cost	0	+	+	-	-	-
Easy to manufacture	0	+	-	-	-	0
Ability to pull in and push out fluid	0	+	+	+	+	+
Turbulent flow	0	+	+	+	+	+
Increase heat transfer rate	0	+	+	+	+	+
Low noise	0	+	0	0	0	0
Operate at varying frequencies	0	+	+	+	+	+
Durable	0	0	-	0	+	+
Sum +'s	0	8	5	4	5	6
Sum -'s	0	0	-2	-3	-3	-1
Net Score	0	8	3	1	2	5
Continue?	No	Yes	Yes	No	No	Yes

As shown in Table 2, scores were set to determine the importance of each functional concept. The last rows of each table were used to determine if the functioning concept would be continued on within the design process dependent on their net score and rank. It was concluded that concepts 1, 2, and 5 would be taken into further consideration with weight factors. The selection criteria were then rated using an AHP's rating for pairwise comparison.

## AHP's Rating

The **Analytic Hierarchy Process (AHP)** is an effective tool for dealing with complex decision making, and may aid the decision maker to set priorities and make the best decision. The purpose of these ratings is to obtain the weights for selection criteria for the final rankings. These rating guidelines will be used to narrow down the top three concepts by comparison and are shown below in Table 4.

Table 4.3 AHP's Ratings for Pairwise Comparison of Selection Criteria.

<b>Rating Factor</b>	<b>Relative Rating of Importance Between 2 Selection Criteria A and B</b>	<b>Explanation of Rating</b>
.11	B is highly more important than A	B is highly more important than A
.14	B is more important than A	B is more important to product success
.2	B is moderately more important than A	B is moderately more important to product success
.33	B is slightly more important than A	B is slightly more important to product success
1	A and B are equally important	A and B hold the same importance to the product's success
3	A is slightly more important than B	A is slightly more important to product success
5	A is moderately more important than B	A is moderately more important to product success
7	A is more important than B	A is more important to product success
9	A is highly more important than B	A is highly more important than B

The rating criteria above was used to compare the selection criteria and the results are shown below in the Criteria Comparison Matrix (Table 5). Based on the importance of criteria A or B, the sum of each criteria is displayed at the bottom of the table and will be used to form the basis of the criteria weights.

Table 4.4 Criteria Comparison Matrix

		<b>B</b>								
		<b>Fit in space available</b>	<b>Low cost</b>	<b>Easy to manufacture</b>	<b>Ability to pull in and push out fluid</b>	<b>Turbulent flow</b>	<b>Increase heat transfer rate</b>	<b>Low noise</b>	<b>Operate at varying frequencies</b>	<b>Durable</b>
<b>A</b>	<b>Fit in space available</b>	1	7	3	1	0.33	0.33	9	0.33	3
	<b>Low cost</b>	0.14	1	1	0.11	0.11	0.11	5	0.2	0.33
	<b>Easy to manufacture</b>	0.33	1	1	0.11	0.11	0.11	5	0.14	1
	<b>Ability to pull in and push out fluid</b>	1	9	9	1	1	1	7	3	7
	<b>Turbulent flow</b>	3	9	9	1	1	1	9	3	7
	<b>Increase heat transfer rate</b>	3	9	9	1	1	1	7	3	7
	<b>Low noise</b>	0.11	0.2	0.2	0.14	0.11	0.14	1	0.14	0.2
	<b>Operate at varying frequencies</b>	3	5	7	0.33	0.33	0.33	7	1	5
	<b>Durable</b>	0.33	3	1	0.14	0.14	0.14	5	0.2	1
	<b>Sum</b>	<b>11.91</b>	<b>44.2</b>	<b>40.2</b>	<b>4.83</b>	<b>4.13</b>	<b>4.16</b>	<b>55</b>	<b>11.01</b>	<b>31.53</b>



The comparison matrix shows the strengths of criteria A with respect to criteria B. For instance, “fit in space available” is of equal importance to “fit in space available”, while “fit in space available is more important “low cost”. The importance of “turbulent flow” is highly more important than “low noise”, and “increase heat transfer rate” is highly more important than “easy to manufacture”. A high value sum represents that criteria A is more important, and a low value sum represents that criteria B is more important. This chart maps out the positive and negative correlations between two criteria that are not easily perceived and helps with the process of determining the criteria weights.

The numbers displayed in Table 5 do not clearly represent the importance of each of the criteria, so the table was normalized in order to display a direct comparison of concept to concept. The way that the numbers were normalized were by taking each of the criteria listed in the chart and dividing it by the sum of all of the values in its respective column. After each new column was completed, the column was summed in order to confirm that it was equal to one. Having all of the selection criteria in respect to one directly compares the criteria to one another. The normalized criteria are shown in Table 6. The average of each of the selection criterias are listed on the far left column; this is the number that is most important in deciding top criteria.

Table 4.5. Normalized Criteria Comparison Matrix

		<b>B</b>									
		<b>Fit in Space Available</b>	<b>Low Cost</b>	<b>Easy to Manufacture</b>	<b>Ability to Pull in and Push Out Fluid</b>	<b>Turbulent flow</b>	<b>Increase Heat Transfer Rate</b>	<b>Low Noise</b>	<b>Operate at Vary Frequencies</b>	<b>Durable</b>	<b>Average</b>
<b>A</b>	<b>Fit in Space Available</b>	0.08	0.16	0.07	0.21	0.08	0.08	0.16	0.03	0.10	<b>0.11</b>
	<b>Low Cost</b>	0.01	0.02	0.02	0.02	0.03	0.03	0.09	0.02	0.01	<b>0.03</b>
	<b>Easy to Manufacture</b>	0.03	0.02	0.02	0.02	0.03	0.03	0.09	0.01	0.03	<b>0.03</b>
	<b>Ability to Pull in and Push Out Fluid</b>	0.08	0.20	0.22	0.21	0.24	0.24	0.13	0.27	0.22	<b>0.20</b>
	<b>Turbulent Flow</b>	0.25	0.20	0.22	0.21	0.24	0.24	0.16	0.27	0.22	<b>0.23</b>
	<b>Increase Heat Transfer Rate</b>	0.25	0.20	0.22	0.21	0.24	0.24	0.13	0.27	0.22	<b>0.22</b>
	<b>Low Noise</b>	0.01	0.00	0.00	0.03	0.03	0.03	0.02	0.01	0.01	<b>0.02</b>
	<b>Operate at Varying Frequencies</b>	0.25	0.11	0.17	0.07	0.08	0.08	0.13	0.09	0.16	<b>0.13</b>
	<b>Durable</b>	0.03	0.07	0.02	0.03	0.03	0.03	0.09	0.02	0.03	<b>0.04</b>
	<b>Sum</b>	1	1	1	1	1	1	1	1	1	<b>1.00</b>

The other necessary characteristic for the final rankings was the rating factor, which is based on a 3, 4, and 5 scale. This rating represents the importance of each of the criteria to each

of the designs, or concepts, created. Table 2 was used in determining the weight of the criteria to each concept. Table 7 shows what each of the three rankings represent.

Table 4.6. Rating Factors

<b>Rating Factor</b>	<b>Explanation of Rating</b>
3	Reaches the criteria
4	Moderately exceeds the criteria
5	Exceeds the criteria

The final table used for concept selection was the Weight Factors Table which compares the normalized number of each criteria to the weight for each of the concepts. This table was created by first listing the selection criteria and the average of their normalized weight from Table 6. Next, the three remaining concepts were listed at the top with their ranking numbers listed in the columns below each of the concepts. The weight score was then calculated for each of the criteria per concept by multiplying the weight of the concept by the ranking for that criteria. The total score was then calculated by adding up all of the weighted scores for each concept. The total scores were used to determine which concepts to go forward with and which one(s) to drop.

Table 4.7. Weight Factors

Selection Criteria	Weights	Concepts					
		1		2		5	
		Rotational Vibration		Discrete Vibration		Piston/Jets	
		Rating	Weight Score	Rating	Weight Score	Rating	Weight Score
Fit in space available	0.108	5	0.5400	4	0.4320	5	0.5400
Low cost	0.028	5	0.1415	5	0.1415	3	0.0849
Easy to manufacture	0.032	5	0.1591	3	0.0955	4	0.1273
Ability to Pull in and Push Out Fluid	0.203	5	1.0127	5	1.0127	5	1.0127
Turbulent flow	0.225	5	1.1262	5	1.1262	5	1.1262
Increase Heat Transfer Rate	0.221	5	1.1059	5	1.1059	5	1.1059
Low Noise	0.016	5	0.0807	4	0.0646	4	0.0646
Operate at Varying Frequencies	0.127	5	0.6352	5	0.6352	5	0.6352
Durable	0.040	4	0.1590	3	0.1193	5	0.1988
<b>Total Score</b>		<b>4.9602</b>		<b>4.7327</b>		<b>4.8955</b>	
<b>Rank</b>		1		3		2	
<b>Continue?</b>		Yes		No		Yes	

The total scores of the concepts reflect that concepts 1 and 5 had scores within a single decimal point of one another, so both designs were looked at going forward; whereas, Concept 2 had a slightly lower score than the other two so it will not be analyzed further. The reason for choosing two final concepts instead of one is due to the human error in the beginning of the decision making process. Early on, Table 5 was created based on the AHP tool, which is

effective but does leave room for human judgement. The small differences in the numbers selected in that chart may have trickled down into the total scores for the final concepts, which was why it was best to go forward with both Concepts 1 and 5 as they are equally as viable at this point. These two concepts were investigated by conducting further research on each of the systems and by having further discussions with the faculty advisor and project sponsor in order to eliminate one and go forward with the design of the other. The details of the two final selected concepts are shown in Table 9.

#### 4.4 Final Concepts

Table 4.8-1. Final Design Concept Combination 1

	<b>Concept</b>	<b>Solution</b>
Energy	Accepts External Energy	Actuator
	Convert Electrical to Mechanical Energy	Electromagnetic
Pulse	Apply Torque to Pulse Device	Shaft Connected to impeller
	Initiates Pulse	Rotational Discrete Vibration
Water	Enters Pulse Device	Pulled
	Becomes Turbulent	Shape of Shaft
	Leaves Pulse Device	Pushed

Table 4.8-2. Final Design Concept Combination 2

	<b>Concept</b>	<b>Solution</b>
Energy	Accepts External Energy	Actuator
	Convert Electrical to Mechanical Energy	DC Electric Motor
Pulse	Apply Torque to Pulse Device	Shaft Connected to impeller
	Initiates Pulse	Pistons/Jets
Water	Enters Pulse Device	Pulled
	Becomes Turbulent	Velocity
	Leaves Pulse Device	Pushed

The device will need to accept external energy to have power and will run off of the pump's power. For both concept combinations, an actuator allows the device to run with the pump and is used to operate the device under different frequencies. This power needs to be converted into mechanical energy so that the device can perform its functions. This will be performed electromagnetically for the first concept and by a DC electric motor for the second concept. For the pulse to be created, torque needs to be applied to the device which is achieved by a shaft connected to the impeller. For the first concept, the pulse is initiated through rotational discrete vibration. For the second concept, the impeller applies rotational motion to pistons, initiating a pulse onto synthetic jets onto a cooling block. In order for the water to enter the pulse device, it has to be pulled in through the opening located at the top of the device. The water then needs to become turbulent which is achieved by altering the shape of the shaft for the first concept and through velocity manipulation for the second concept. The water then leaves the pulse device by being pushed out and onto the cooling block to increase heat transfer. For the sketched diagrams of the final concept combinations, refer to Figures 3.6 and 3.10.

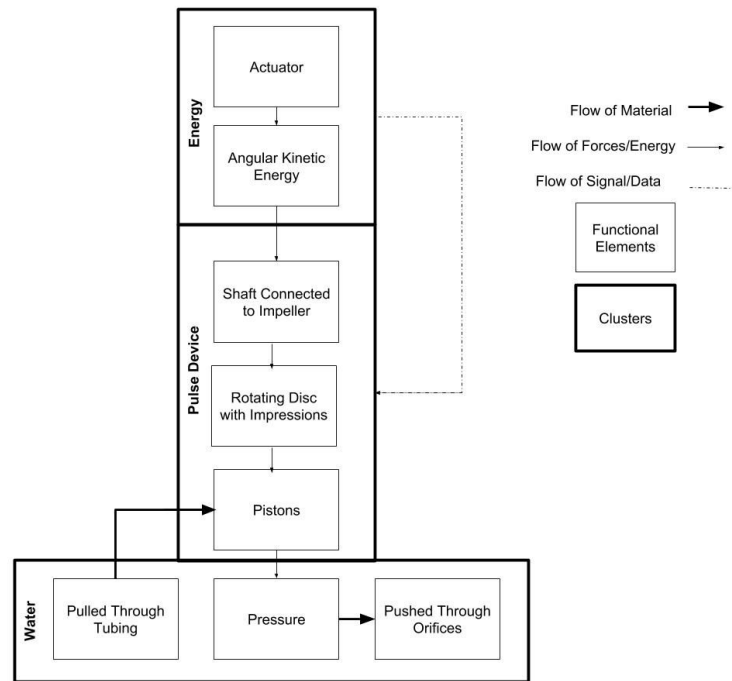
## **5. Product Architecture**

### **5.1. Introduction of Chapter**

With the functional concept defined, the architecture of how this device is intended to be built was analyzed. The product architecture is the scheme by which the functional elements of a product are arranged into physical chunks and by which the chunks will interact. The architecture of this product will influence product development, production system design, manufacturing and assembly, the use by the customer, and ultimately future development. This chapter will describe the product architecture of the design with a detailed schematic and geometric layout of the desired design.

### **5.2 Grouping of Functional Elements**

With the specified final design based upon the functional concepts in previous chapters and modifications based on the industry mentor's feedback, the functional elements schematic diagram was produced, as shown in Figure 5.1. The diagram displays the flow of material, forces/energy and signal/data. The flow of material, which is water, is represented by a thick black line. The flow of forces/energy is represented by a thin black line and the flow of signal/data is represented by a dotted black line. Modular architecture was used for product development and prototyping so that the design can be taken apart, and allows flexibility for change if needed. From the customer perspective and for the final product, this design is to be considered as integrated because of the complexity of the device and in not being feasible to perform part replacement.



**Figure 5.1** Functional Elements Schematic Diagram

The schematic for the functional elements flows from top to bottom. The actuator is activated by the pump which powers the system. The signal runs through the system for the pulse device to operate under different frequencies based on the pump. The actuator flows the energy from the impeller connected to the pump into angular kinetic energy from the shaft connected to the impeller. Attached to the shaft are rotating disks with impressions that translate mechanical energy onto the pistons which causes the pistons to create pressure. The water is pulled into a cavity that is located under the pistons, in which the pressure caused by the pistons allows the water to be pushed out of the pulse device through orifices and onto the cooling block thus inducing turbulence on to the microchannels and increasing heat transfer. The cluster which entails the energy is the main power source of the pulse device and sends the frequency signal at

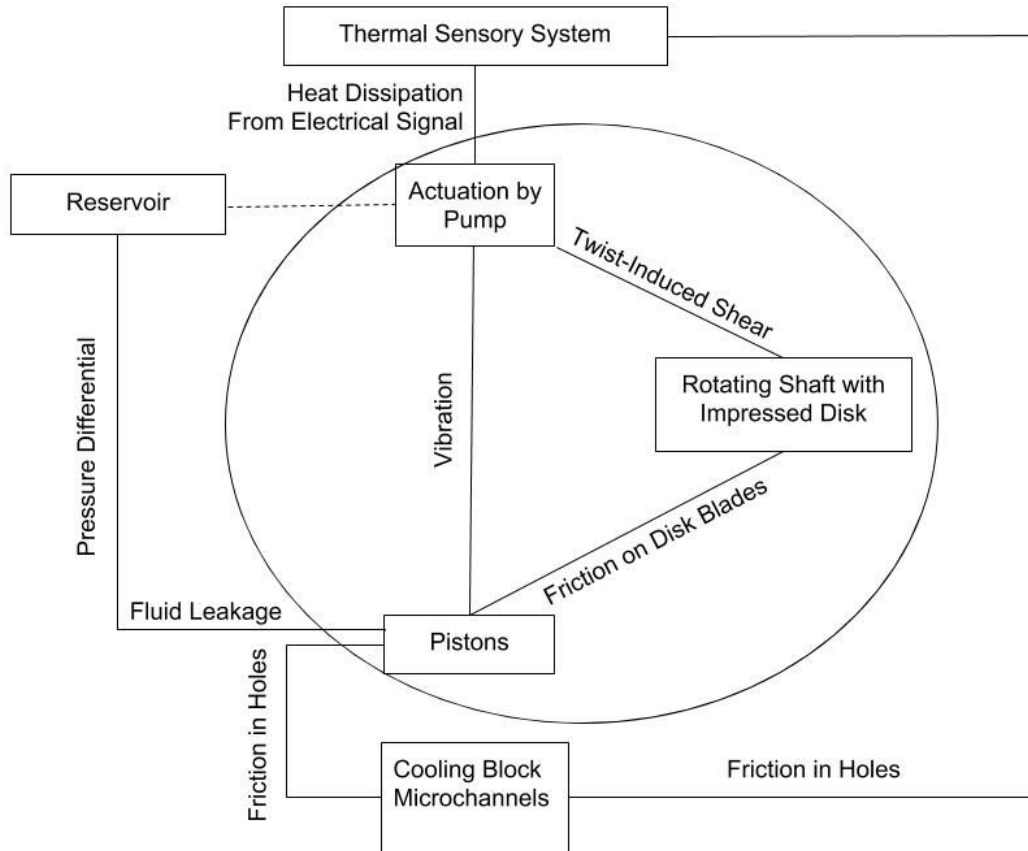


which the pulse device can operate. The shaft, rotating disks, and part of the pistons are clustered together to ensure that no liquid can get inside, as this will cause failure. The cluster through which the water flows enters through tubing from outside of the system and exits the pulse device and back out of the system.

### **5.3 Interaction of Elements**

Interactions between the elements of a system fall into two categories: fundamental and incidental. Fundamental interactions between elements are those which connect the components together and help achieve the desired physical effects. Incidental interactions are those which do not contribute to the cause of the design, but are important to consider for the durability and sustainability of affected components.

Incidental interactions are modeled in Figure 5.2. The oval hones in on the elements particular to the design being generated in this project. When the computer's thermal sensory system emits the electrical signal to the pump to initiate motion, heat is generated; as the pump continues to receive the signal, the heat from the electrical signal is maintained.



**Figure 5.2** Lines of Incidental Interaction

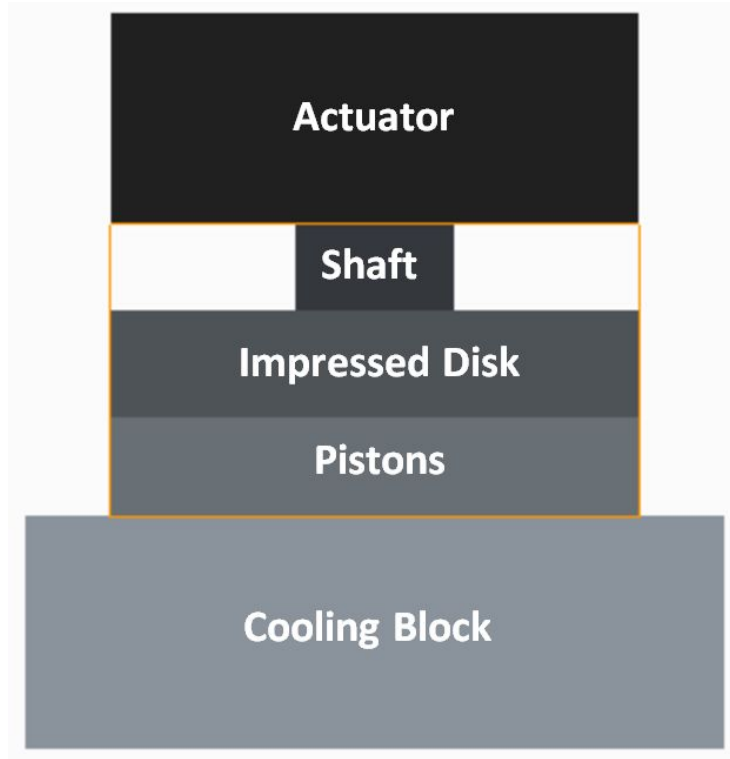
The actuation of the system by the pump causes minute initial shear due to twisting on the rotating shaft. The shaft may encounter very slight resistance within the system (air, leaked fluid, etc) and thus suffer twisting shear at the connection between the pump and the shaft.

The actuation by the pump also results in mechanical vibration which influences the performance and efficiency of the pistons: small translational differences due to vibration result in different amounts of water being pushed by the pistons, and vibration also generally leads to wear of components over time.

Where the impressed disk comes into contact with the pistons, friction is almost certain. With friction comes heat, shear, and general wear of both contacting surfaces. When fluid travels from the reservoir of the pump to the pistons, there is a pressure differential due to the vertical distance and the tube's inner diameter and length. There is also potential for fluid leakage at the connections between the reservoir and the tubing and between the tubing and the pistons. A turbulent flow regime is known to cause friction at pipe connections and within channels: when fluid leaves the pistons to the microchannels of the cooling block, and when the fluid leaves the microchannels for the radiator, there will be shearing at the entry and exit holes. All of these incidental interactions of elements are important to consider, as durability is one of the goals for the final design.

#### **5.4 Geometric Component Layout**

To finalize product architecture, the geometric component layout that shows the final configuration and footprint of the product must be determined. Creating a geometric layout forces a decision of whether the geometric interfaces between the components are feasible or not. The component layout contributes to the modularity of the design as future possible modifications can be determined from the geometric "chunks." The geometric layout is also important to observe any incidental interactions that need to be taken into account before prototyping. From the component layout and incidental interaction, five component chunks were determined based on the overall functions of the parts. This geometric block diagram is shown in Figure 5.3 below.

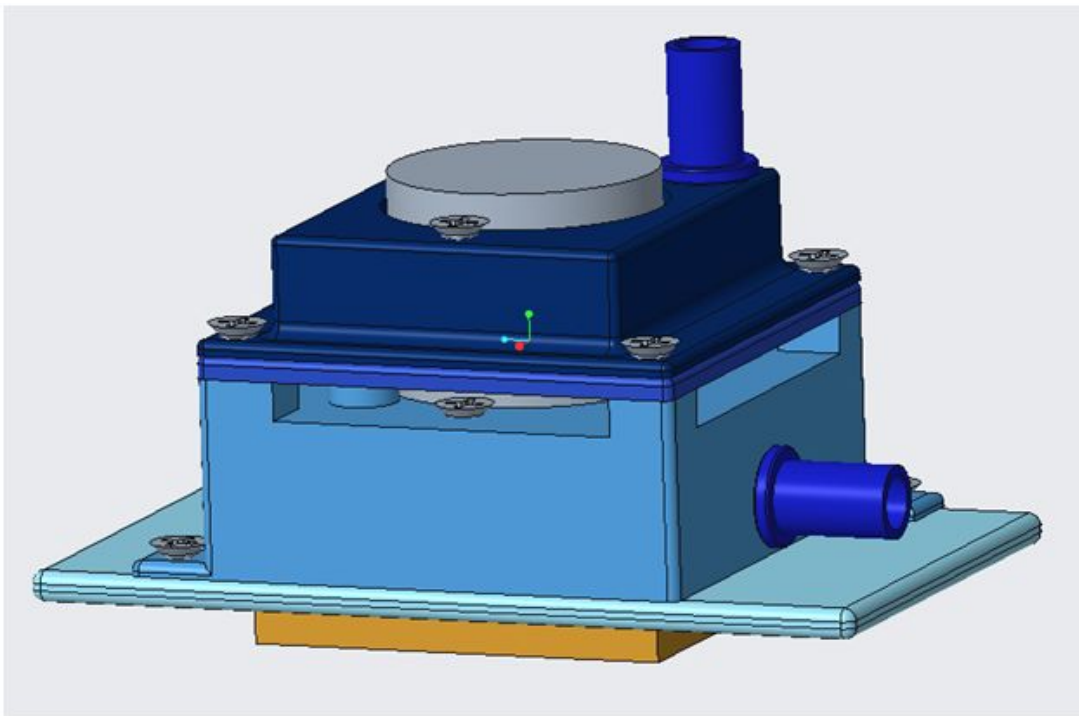


**Figure 5.3** Geometric Block Diagram

The five components shown above are the actuator, shaft, impressed disk, pistons, and the cooling block. These mechanisms are aligned in the block diagram in a way to demonstrate the the desired layout of the pulse device. The actuator input chunk accounts for the pump impellers that will be used to create the minute shear force to the impending shaft. The next block is the shaft that will work to initiate the rotation of the impressed disk. These chunks are the driving force of the system. The piston block will cause displacement in the fluid and in turn cause turbulence through the jets onto the microchannels of the cooling block. The cooling block chunk of the diagram represents the final integrated part of the pre-sealed system where increased heat transfer ultimately takes place. The enclosure encompasses the shaft, impressed disk, and pistons as it will be the basis of the pulse device and in its own encased shell.

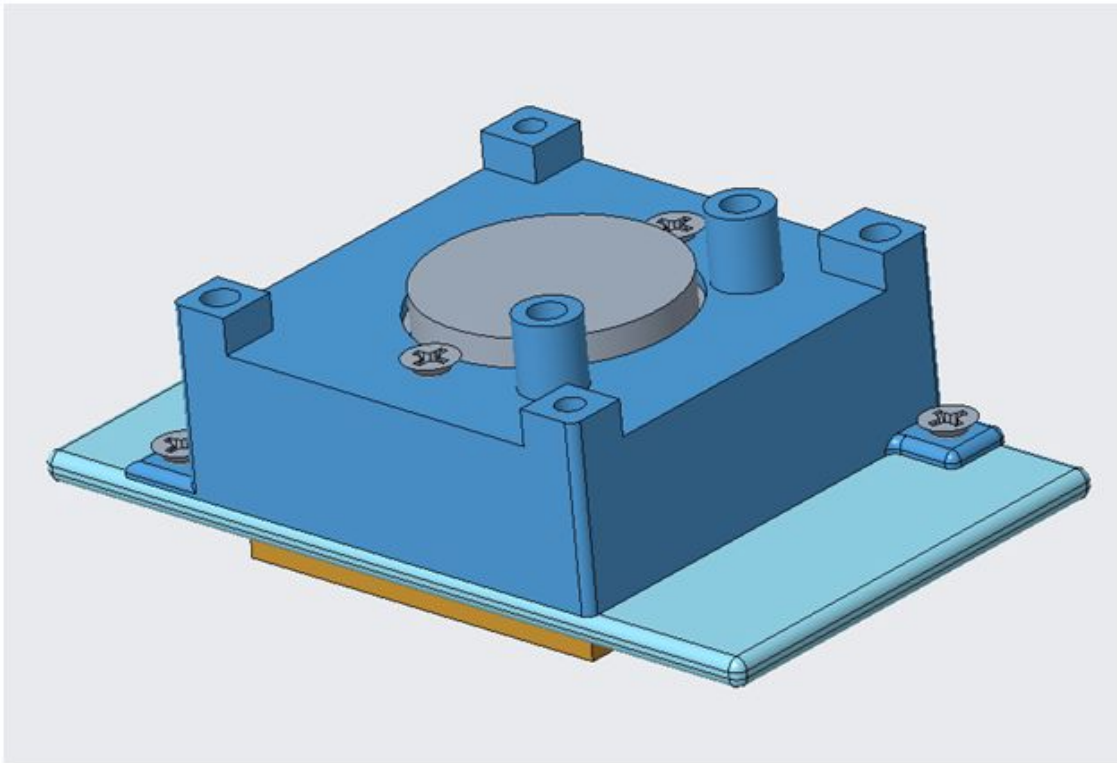
## 5.5 Computer Aided Design Model CAD

The pulse device is integrated into a pre-sealed cooling system, so the CAD (computer aided design) model is divided into different levels in order to help visualize the system. The pump sits on top of the pulse device in a different enclosure, making the pump modular as it can be changed. The outside view of the entire CAD drawing is shown in Figure 5.4 below. The view shows the pump and enclosure, box enclosing the entire pulse device, block with jets and the cooling block. The box that encloses the system is what will seal the entire cooling system as it encloses the water that goes from the pump to the cooling block.



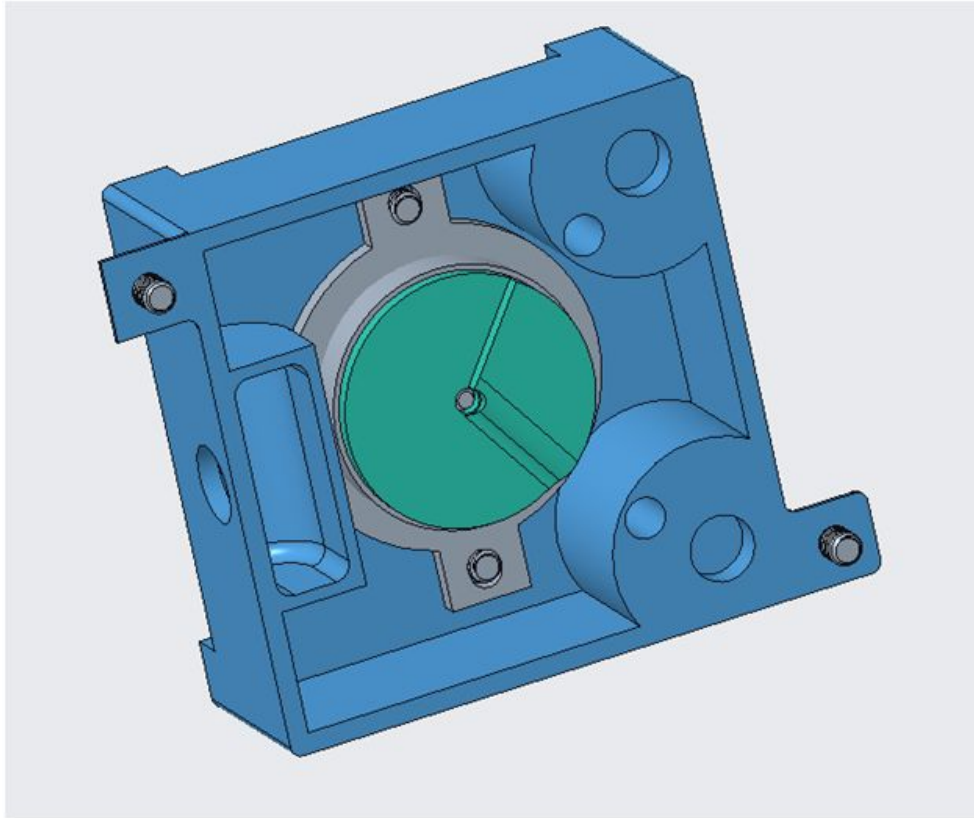
**Figure 5.4** CAD Model - Outside

The next level of CAD drawing (Figure 5.5) is the pulse device which shows only the integrated enclosure around the pulse device that keeps it sealed. It is imperative to seal the pulse device from the surrounding water so that the pistons do not get water in them. This view of the model also shows the relationship of the pulse device and the cooling block.



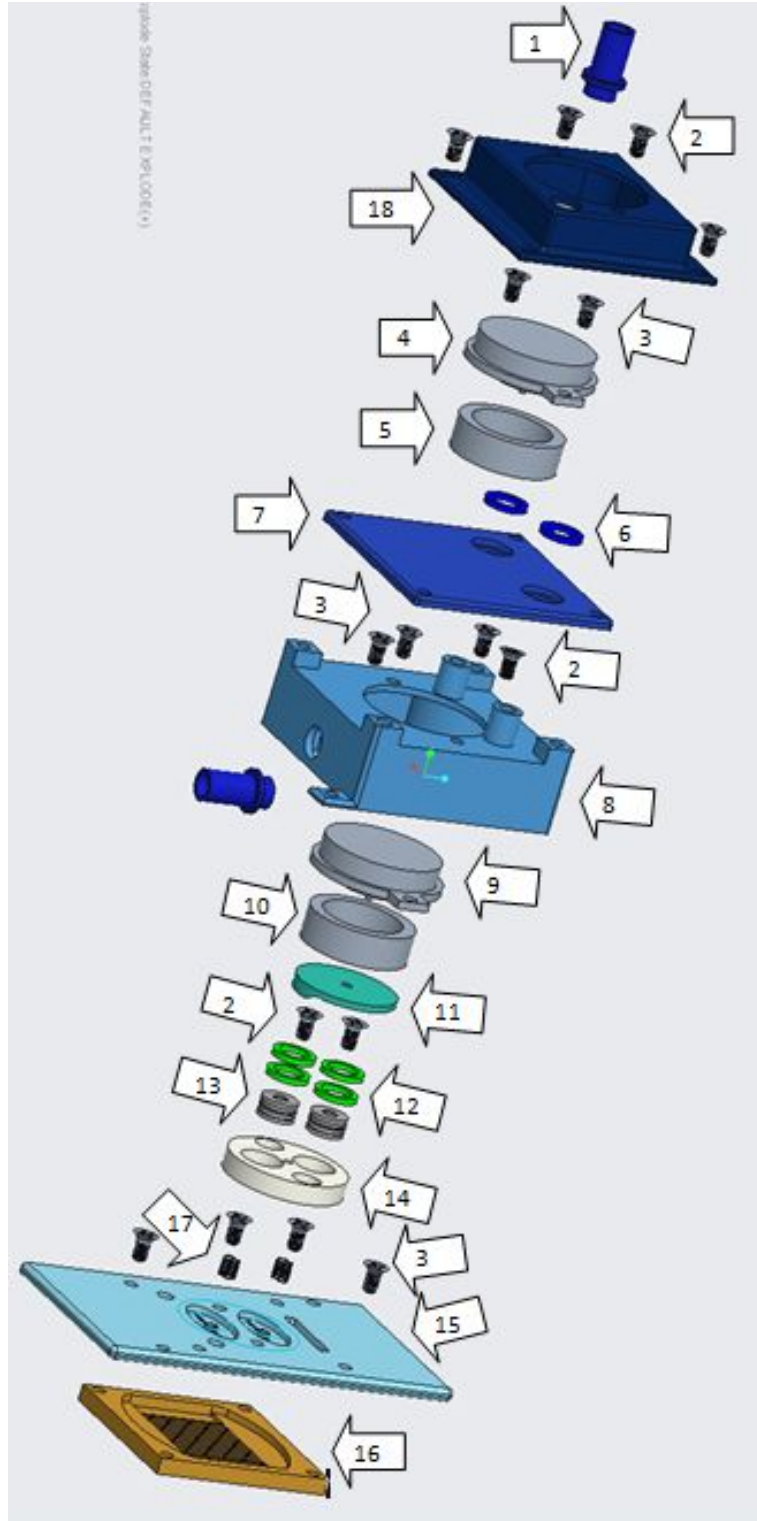
**Figure 5.5** CAD Model - Pulse Device

The third view, Figure 5.6, of the model is the inner view which shows the pulse device itself. This view shows the small shaft that protrudes from the pump and connects to the wider shaft on the rotating disk. The rotating disk has blades on the bottom that “hit” the piston in the cylinder, causing it push down on the water, creating a pulse.



**Figure 5.6** CAD Model - Inner

Figure 5.7 shows the exploded view which supplies every component of the CAD model separated from one another so the full parts are shown. Every component of the model is labeled below.



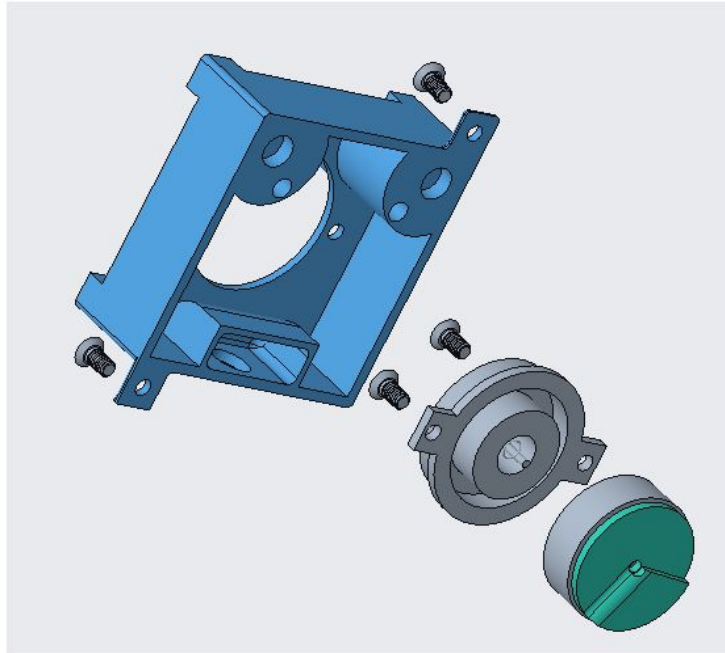
**Figure 5.7** CAD Model - Exploded



Legend:

1. Hose Fitting
2. Sealant Screws
3. Screws
4. 2600 Motor
5. Pump With Impellers
6. O-Rings
7. Enclosure B
8. Enclosure A
9. 3600 Motor
10. Pump Without Impellers
11. Rotating Disk
12. Square O-Rings
13. Pistons
14. Cylinder
15. Jet Block
16. Cooling Block
17. Springs
18. Enclosure C

The last view is an exploded view of just the pulse device so the details of it is shown clearly. Figure 5.8 shows the enclosure A, 3600 motor, pump without impellers, rotating disk, and the respective hardware.



**Figure 5.8** CAD Model - Exploded Pulse Device

The detailed view of the final concept clarifies the product architecture considerations of functional element groups and elemental interactions to fulfill the needs of the final design.

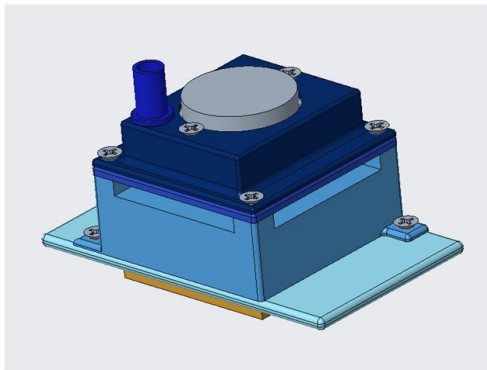
## 6. Engineering Analysis

### 6.1 Introduction of Chapter

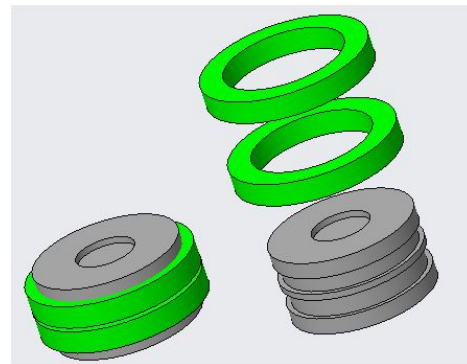
An engineering analysis is required to ensure proper performance of the selected design. An engineering analysis involves the breakdown of a conceptual design into mechanisms of operation or failure to reveal the properties and state of a system. This analysis provides a demonstration that the design concept could achieve the required functions. A computational fluid dynamics simulation program, Star-CCM+, was used for a complete heat transfer analysis throughout the system.

### 6.2 Analysis Approach

The final design concept consists of a rotating disk attached to a centrifugal pump that actuates a piston system. The pistons push water onto the cooling block, inducing turbulence and enhancing the heat transfer of the overall liquid cooling system. This pulse device is integrated into a pre-sealed cooling system that is 3D printed with ABS filament. The final concept is shown in Figures 6.1a and 6.1b.



**Figure 6.1a. Final Concept**



**Figure 6.1b. Piston Subassembly**

It should be noted that a variety of different parameters were to be adjusted for certain conditions in application for this project. This was important in the process of testing conditions and what assumptions were made in the engineering analysis. Based on overall liquid cooling systems and fluid flow properties, the following assumptions were made:

- Heating comes from two possible directions: from the bottom of the cooling block, where the CPU contacts the cooling block, and from the insides of the microchannel walls, where friction creates heat as a result of the fluid moving between the walls.
- The flowing fluid is incompressible and homogeneous. Water has uniform properties throughout, and the density is constant within the given fluid parcel.
- The flowing fluid is expected to be laminar as it enters the closed-loop system, with a Reynolds number below 2300.

The analysis was to be tested under both static and dynamic testing conditions. With static testing, the system is run under constant parameters. This allows for an analysis of long use of the system under different parameters in order to predict energy consumption, heat, and vibration. With dynamic testing, the system is run under more intense/varying parameters. This simulates how the system operates under heavy stress, and predicts stress's effect on the system's energy output. The outcomes of these tests were to determine the system's durability and effectiveness under varying parameters. The varying parameters tested include:

- Testing heat dissipating from the cooling block at different temperatures
- Pressure drop from the pistons pushing the water through the jets
- Velocity at jet inlets and across the microchannels of the cooling block

### 6.3 Governing Equations

The total energy loss through the microchannels was first calculated. Total loss considers both head loss (due to the geometry of the channels) and frictional losses. In this case, major loss is caused by the friction through the microchannels, which is likely to account for over three quarters of the total loss. Total loss is dependent on velocity through the microchannels, which is represented by:

$$V = \sqrt{2 * g * h} \quad \text{Eq. 7}$$

*g* = constant of gravitational acceleration, (9810 mm/s<sup>2</sup>)  
*h* = height of microchannels (mm)

Equation 7 is the application of conservation of energy to a fluid, because the sum of the kinetic energy and potential energy is zero.

The equation for total loss is then given by Equation 8:

$$\Delta h_f = [f * (\frac{L}{D}) + \Sigma k] * (\frac{V^2}{2 * g}) \quad \text{Eq. 8}$$

*f* = friction factor (from Moody chart)  
*L* = length of channel (mm)  
*D* = hydraulic diameter, or in this case, the wetted cross-sectional area (mm<sup>2</sup>)  
*k* = minor loss coefficients, dependent on geometry of microchannels (unitless)  
*V* = velocity (mm/s)  
*g* = constant of gravitational acceleration, (9810 mm/s<sup>2</sup>)

Next, the flow area is determined. This is the area of all of the jet holes through which the fluid will pass, found using Equation 9.

$$A = N * (\pi * r^2) \quad \text{Eq. 9}$$

$N = \text{number of holes}$

$r = \text{radius of hole}$

The pressure differential across the jet holes is then determined using the velocity in Equation 7 and Equation 10.

$$\Delta P = f * \frac{l}{D} * \frac{\rho V^2}{2} \quad \text{Eq. 10}$$

$f = \text{friction factor}$

$l = \text{height of hole}$

$D = \text{hole diameter}$

$\rho = \text{density of water } (10^{-6} \text{ kg/mm}^3)$

After determining the pressure differential, the thermodynamic table of compressed water and superheated steam needs to be consulted in order to ensure that vaporization has not occurred.

The flow area and pressure differential together, represented by Equations 9 and 10 respectively, are used to determine the force exerted by the system for the pressure differential to come into effect, given in Equation 11.

$$F = A * \Delta P \quad \text{Eq. 11}$$

$A = \text{Area}$

$$P = \text{Pressure}$$

The counteracting force by the piston is equal to the force exerted by the system. This force value can be used to determine the work by the piston on the system, given by Equation 12.

$$W_p = F * d \quad \text{Eq. 12}$$

$$d = 0.5 * \text{length of cooling block}$$

The fluid enters the cooling block with the force supplied by the piston, which gives a value of work determined by Equation 12. When the fluid exits the block, it must be pushed with a greater force than that with which it entered the block, since the pressure differential will have decreased. Therefore, the work of the spring can be represented by Equation 13.

$$W_s = 2 * W_p = -\frac{1}{2} * k * x^2 \quad \text{Eq. 13}$$

$$k = \text{spring constant}$$

$$x = \text{distance piston will travel}$$

The power of the system is computed using values from Equations 7 and 11.

$$\text{Power} = F * V \quad \text{Eq. 14}$$

The flow rate is the amount of fluid which passes through the holes multiplied by the frequency at which it does so. The volume of a singular hole uses the flow area calculated in Equation 9 to yield Equation 15:

$$V_{hole} = A * l \quad \text{Eq. 15}$$

Since frequency is known to be the inverse of elapsed time, the flow rate can thusly be calculated with Equation 16.

$$Q = V_{hole} * \frac{1}{t} \quad \text{Eq. 16}$$



<b>Variables</b>			<b>Specs of Cooling Block</b>			<b>Spring Specs</b>		
Velocity (V)	198.0504986	mm/s	Length	42	mm	Spring constant (k)	0.5	
Frequency (f)	0.05		Width	42	mm	Work of spring (Ws)	2.25	Nm
time (t)	20	seconds	Height	13.0565	mm			
Friction Factor (f)	0.019							
Pressure Drop ( $\Delta P$ )	2.05E+03	N*s/mm						
Force (F)	2.58E+04	N						
distance of Piston action (d)	21	mm						
Total Work (W)	1.08E+06	Nm						
			<b>Hole Specs</b>			<b>Piston Specs</b>		
<b>Constants</b>			height (l)	2	mm	Diameter	10	mm
Density (rho)	0.000001	kg/mm <sup>3</sup>	diameter (D)	1	mm	Height	3	mm
gravity (g)	9806	mm/s <sup>2</sup>	radius (r)	0.5	mm	Height of Cylinder	6	mm
Dynamic Viscosity of Water ( $\mu$ )	8.90E-10	N/mm <sup>2</sup>	Area of one hole	0.7853975	mm <sup>2</sup>	piston distance (x)	3	mm
Pipe roughness	0.0015	mm	Flow Area (A)	12.56636	mm <sup>2</sup>	Work of Piston (Wp)	1.08E+06	Nm
Absolute Roughness			Flow Rate	1.256636	mm/s	# Pistons	2	
Coeff of Plastic	0.0015	mm	# holes (N)	16				
Kinematic viscosity of water??	9.55E-01		Volume of Hole (V)	25.13272	mm <sup>3</sup>			
<b>Pipe/Fluid</b>								
Reynold's Number	1.80E+09							
Relative Roughness	1.50E-03							
Velocity based on flow rate	1.60E+00							

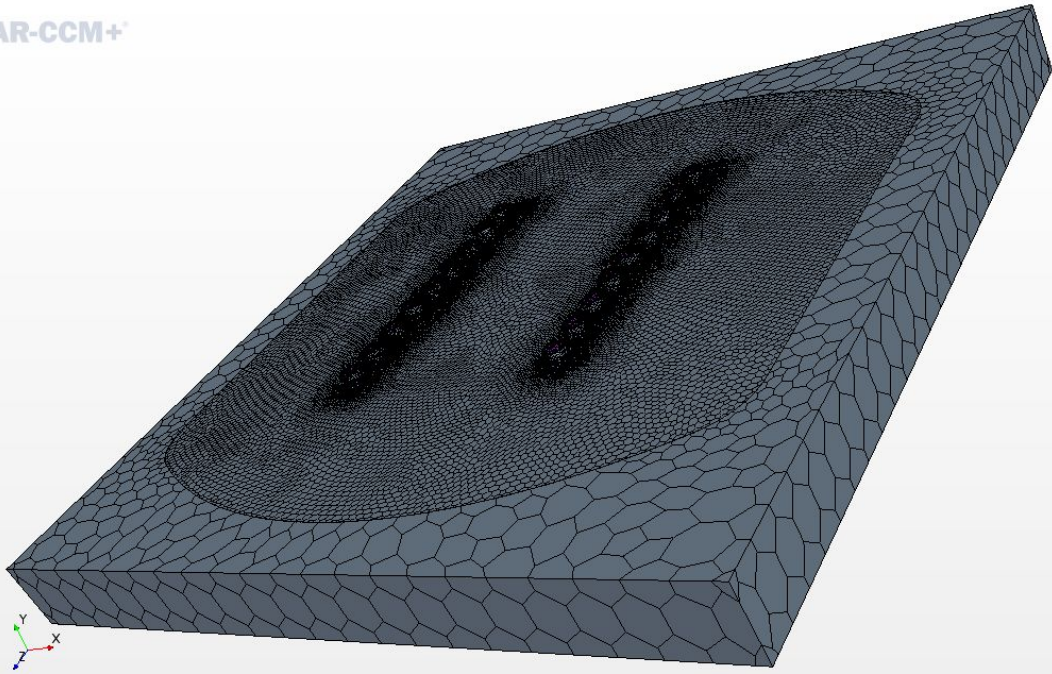
**Figure 6.2.** Calculation Results

A spreadsheet in Microsoft Excel was used for the calculations. Figure 6.2 above shows a sample calculation with provisional values for variables such as velocity, time, pressure drop, force, total work, and Reynold's number.

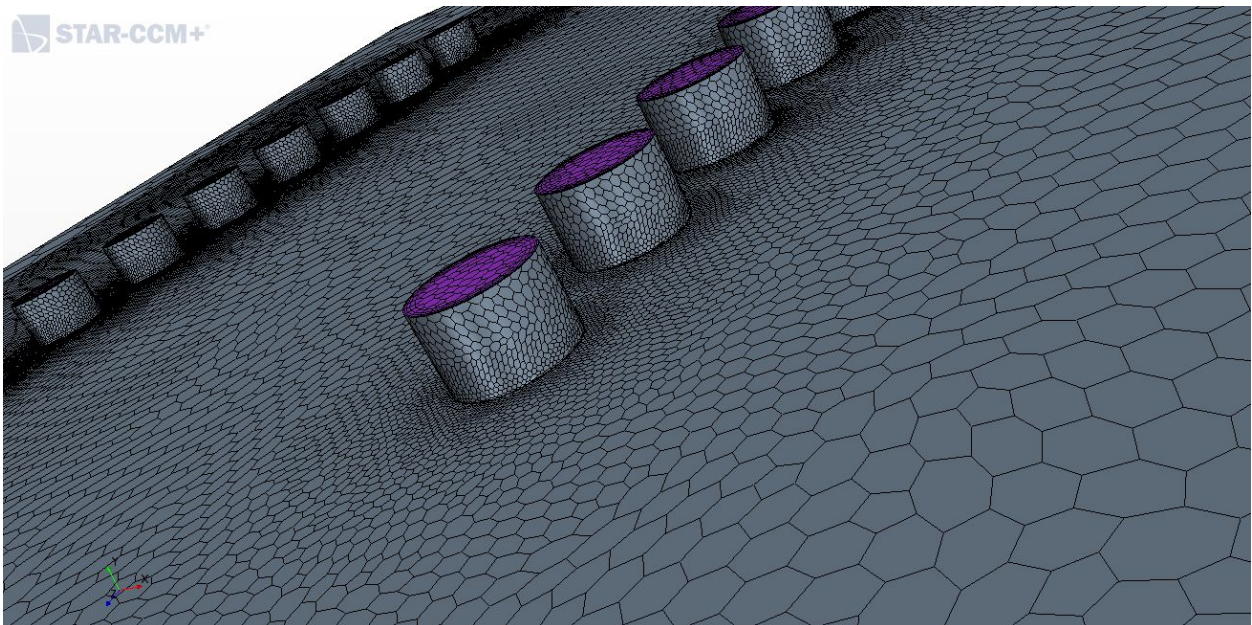
## 6.4 Outputs

The outputs of the simulation can each be analyzed and manipulated by changing the initial parameters. These outputs include heat transfer, velocity, temperature, pressure, and

turbulent flow measured across the microchannels of the cooling block. The heat transfer output was the most important aspect in this design. The simulation of the design allows for a complete analysis to determine critical points such as the efficiency of the heat transfer in higher temperatures and through different frequencies which will test for the efficiency of the design. The software used was a computational fluid dynamics program, Star-CCM+. The approach for analysis was to import the CAD parts, define the fluid volume for which the water flows in and out of, create separate meshes for the fluid boundary as well as the solid boundary, then set parameters and physics models/values to different regions, and finally run the simulation displayed under created scalar and vector scenes. The pressure of the fluid exiting the holes is defined as the function  $A \cdot \sin(\omega t)$  with the pulses being a function of time.  $A$ , represents the amplitude or the force in newtons.  $\omega$ , represents the frequency which is converted into radians by multiplying by  $2\pi$ . Using the calculations from the above results in Figure 2, the pressure for the simulation used was  $22.22 \cdot \sin(2\pi \cdot 43.33 \cdot t)$ . The time is varying according to how long the pulses need to run for.

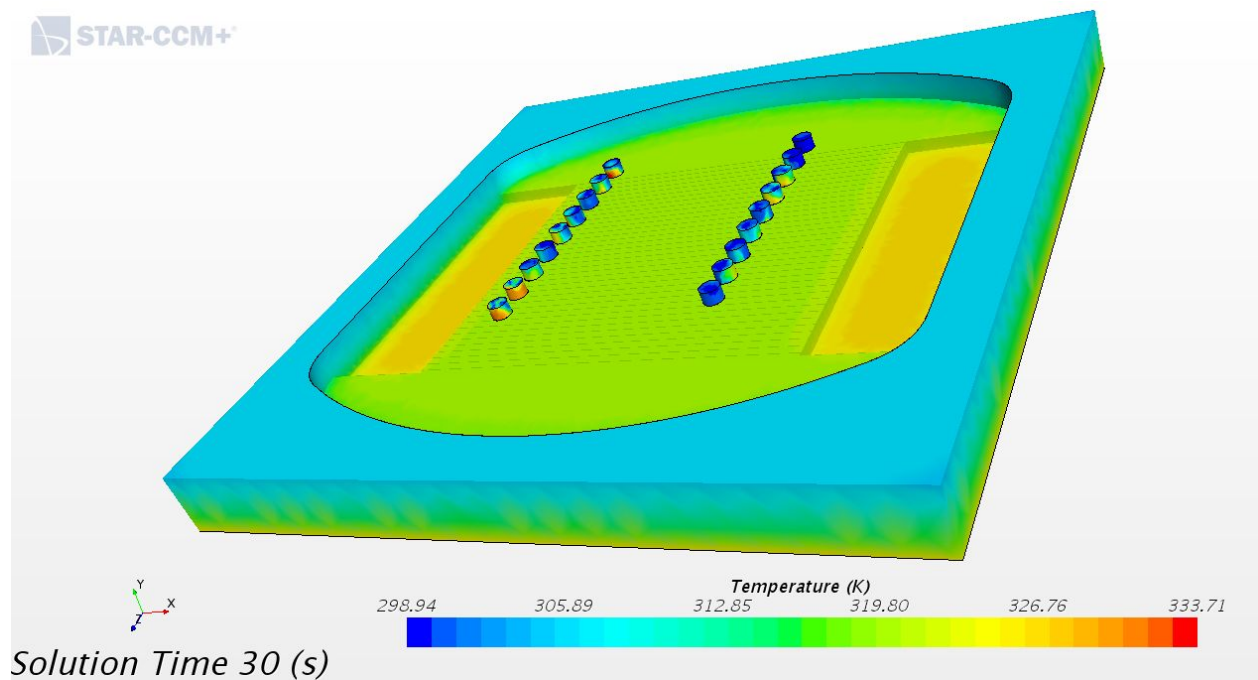


**Figure 6.3.** Full Cooling Block Mesh



**Figure 6.4.** Cooling Block with Meshes Surrounding Jet Holes

Figure 6.3 shows the meshes surrounding the cooling block and Figure 6.4 shows a closer view of the jet holes in which the fluid will be entering and exiting. Inside of this is another mesh containing the fluid boundary. The meshes need to be set up based on the boundaries' geometries so that the simulation can perform with a high degree of accuracy. They allow for the simulation to measure the outputs under the different parameters and conditions.

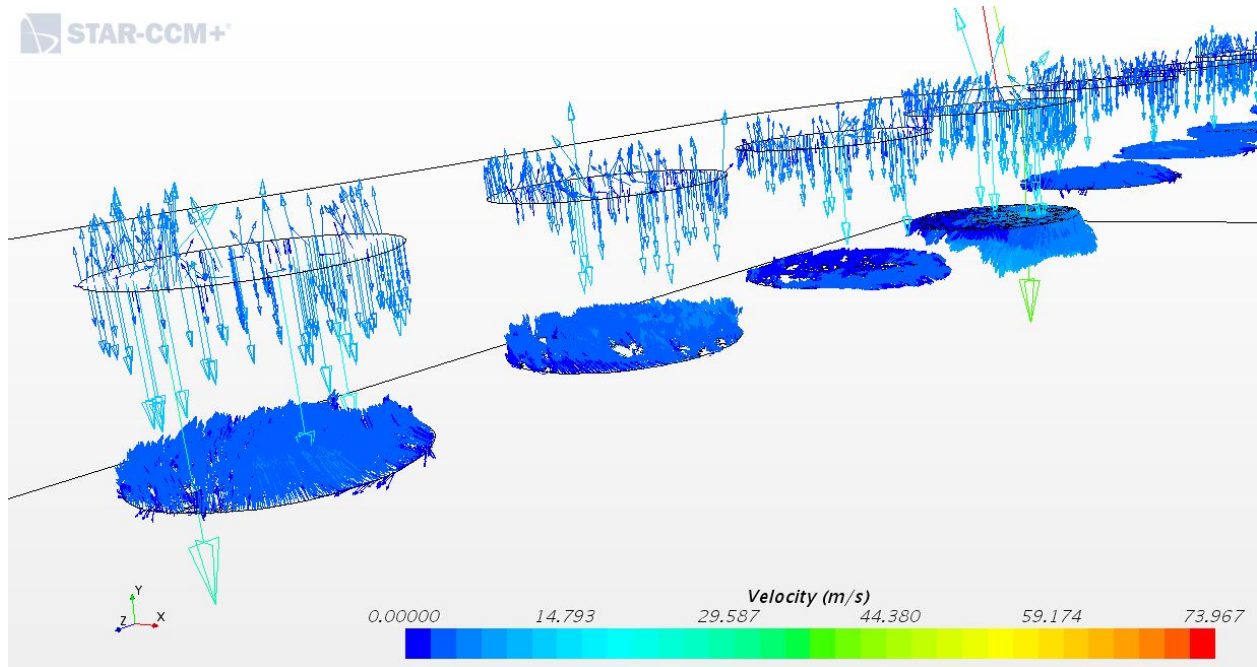


**Figure 6.5.** Temperature Scalar Field

Figure 6.5 shows the temperature scalar field of the geometries being measured. The hottest areas are the bottom of the cooling block which come in direct contact with the CPU. As the fluid enters the holes at a cooler temperature, the heat is dissipated across the microchannels which is apparent by the color gradient as shown in the above figure. The mixed colors in the jet holes indicate the mixing of the cooler and hotter fluid which is from the pulsing of the system as

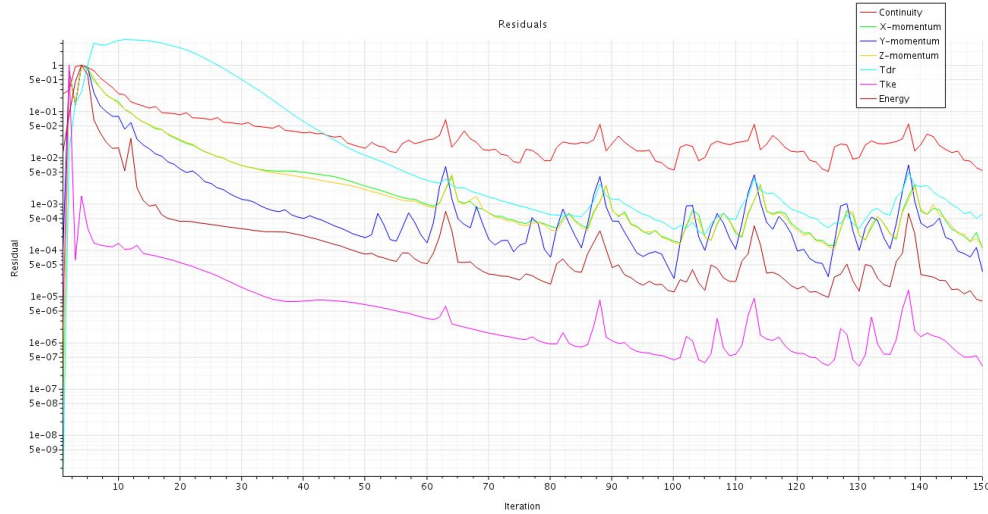


the fluid is being pushed in and out. The heat source or initial temperature of the cpu was set to be 55°C.



**Figure 6.6.** Velocity Vectors

Figure 6.6 shows the relative velocity vector field of the input holes of the water being measured. As shown, the vectors being pushed out of the holes are both random in length and magnitude, thus inferring that the increase in velocity is inducing turbulent flow. Velocity vectors is shown as going both ways which indicates the pulsing of the fluid as it is being pushing in and out through the jets.



**Figure 6.7.** Residuals of Heat and Energy of the Simulation

Figure 6.7 shows the residuals of the heat and energy of the simulation. This is a good visual for representing the overall heat and energy of the simulation. It indicates the reduction in heat of the simulation.

## 6.5 Results

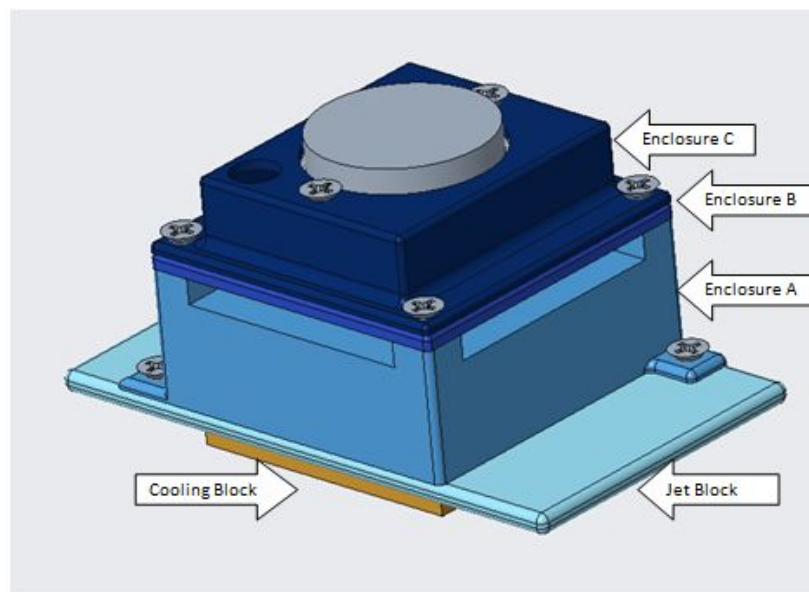
As is apparent in Figure 6.7, the overall heat of the system decreased over time as the simulation took place. The initial steady decrease of the heat indicates that immediate heat transfer takes place. Then, it levels out as the system maintains a steady temperature which demonstrates the proper function of the pulse device. The temperature across the microchannels was found to be  $44^{\circ}\text{C}$  which is  $11^{\circ}\text{C}$  lower than the initial temperature of  $55^{\circ}\text{C}$ . This equates to a 20% reduction in heat which proves the efficiency of the design and the effectiveness of turbulent flow to increase heat transfer. Due to the complexity of the simulation, there were limitations to the analysis of the design.

## 7. Manufacturability

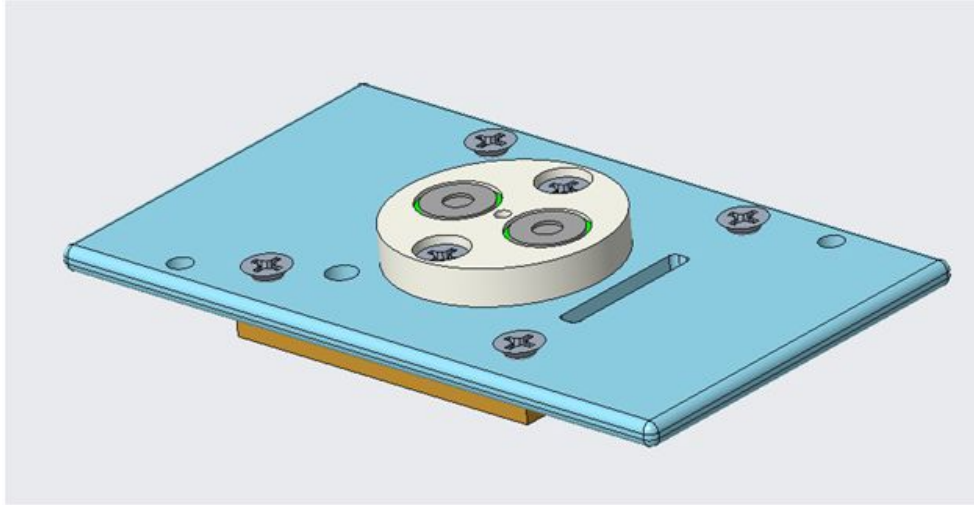
### 7.1 Design for X

#### 7.1.1 Introduction of Chapter

The next step in the process was to refine the design categories of goals to be met to minimize cost and maximize quality. The process of refining the design for different categories of goals is also referred to as Design for “X” or DFX. The DFX outlines how to address potential issues of the product over the course of its lifecycle from design to development to disposal. Exploring these parameters enables the design to be streamlined for efficiency while preserving the value of each component. The relevant X’s for this design were manufacturing, cost minimization, environment, ergonomics, and assembly. Figure 7.1 shows the outer view of the entire pulse device and Figure 7.2 shows the view of the device without the exterior box; showing the interior piston and cylinder setup.



**Figure 7.1.** Pulse Device Exterior View



**Figure 7.2.** Pulse Device Interior View

### **7.1.2 Design for Manufacturing**

Designing for manufacturability is creating the fabrication and manufacturing process to minimize cost while maximizing efficiency. This idea of manufacturability ties together the processes of designing and physically creating the product so that they work together hand in hand. This section discusses how to manufacture the pre-sealed pulse device with minimal material and high efficiency. The primary way that the pulse device was fabricated is by the additive process of 3D printing using a printer that belongs to the Ice Dragon Company. The parts that will be 3D printed will be made of Acrylonitrile Butadiene Styrene (ABS) plastic which was selected for its high temperature durability, high tolerance, and low cost. The parts made of ABS are the jet block, rotating disk attached to motor, and enclosure box for sealing.

Flexibility of 3D printing allows details of the design to be easily modified while maintaining the same product specifications. A 3D printer adapts to the design it is given, so there are no extensive changes to the manufacturing process if an altered design were adopted.



for the pulse device. As far as the design of each part, the corners are rounded so there are minimal sharp edges, which saves material. The only parts that are not rounded are the sides and edges that are designed to fit directly onto other parts; in this case, rounding would decrease the ability of the parts to fit well together. In the design there are holes in accessible locations so that small screws can be inserted during the assembly process and then used for mounting the pulse device onto the copper block. The specifics of how the device is mounted are discussed in the assembly instructions.

The main parts that were not printed were the two pistons and the cylinder that holds the pistons. The cylinder was made of Polytetrafluoroethylene (PTFE/Teflon). The Teflon part was fabricated in the USC machine shop using a lathe, which is the preferred tool for round objects like the cylinder. Teflon was selected for its strength and smooth finish, which allows for the pistons to slide smoothly in the cylinder. The Teflon was purchased as a cylindrical rod of the exact diameter as the cylinder so that the outside did not have to be machined. The pistons were machined from a steel rod of  $\frac{1}{2}$  inch diameter. The rod was cut to the correct height of the piston, 8 mm, and then a lathe was used to create the cutouts on the sides of the pistons. The other parts that were not printed or donated were the sealing and hardware, like the o-rings, piston seals, and screws.

These ideas for the minimization of material were determined only after prototyping and testing, because the integrity of the original design was to be established before any reductions were made.

### 7.1.3 Design for Cost

Minimizing the cost of a product is an integral part of the design process. By assessing the necessary components, manufacturing inputs and outputs, and assembly costs, a design can be altered to ensure that the finalized product will provide a sufficient profit. The design for the pulse device was determined to be relatively cost-efficient based on the low cost of materials and manufacturing for each component. Materials used for the design included low-cost ABS plastic 3D-printing filament and PTFE rods, which can be bought in bulk so that most components can be 3D-printed from a single spool of filament or machined from a single Teflon rod. This standardizes the manufacturing process, with fewer processes simplifying the overall process control.

Another consideration for cost minimization is the reduction of assembly costs. Because the majority of the device was 3D-printed, the number of parts was reduced and assembly is as simple as screwing the printed materials together. When designing the assembly, the orientation of each part must remain constant to allow for any modifications which may arise from the prototyping phase. This constant part orientation was necessary for the implementation of a 3D printer, because the additive process always builds from the bottom up.

The modularity of the design allowed for components to be used in several different products and standardizes component design. The pulse device was standardized so that it can be added or removed from any CPU cooling system and pump. This eliminates the need for manufacturing an entire pre-sealed system for each device and further minimizes costs.

#### **7.1.4 Design for Environment**

Plastic is one of the most abused substances in modern manufacturing. The use of 3D printing plastic for the manufacturing of Ice Dragon's pulse device product therefore brings attention to the topic of environmental awareness. In today's global climate crisis, every product's full lifespan should be considered, from material acquisition through disposal. The Ice Dragon pulse device will primarily be made of ABS plastic, a non-toxic, opaque, thermoplastic, amorphous polymer; and PTFE, a smooth, hydrophobic, synthetic fluoropolymer. Thermosets and thermoplastics make up the majority of polymer types used for manufacturing. Thermosets can be heated to their melting points once, and will suffer irreparable burns if heated to the same or higher temperature a second time. Conversely, thermoplastics can be heated to their melting points, cooled, and reheated to high temperatures without suffering any significant degradation to the material. This property of thermoplastics allows them to be easily recycled. ABS is of the thermoplastic type, and is easy to 3D print and is completely recyclable.

The plastic recycling process involves cutting the old plastic into chips or shreds, then passing the chips through a water-stream separation process. For ABS, the most efficient process used is that of forth-flotation, in which high-purity plastics are separated by water streams from a mix of plastics. However, ABS can also be processed using a single stream separation method, which is common in metropolitan recycling companies. ABS sometimes has its own recycling code, but in the United States fits into recycling code #7, "All Other Plastics". This is fortunate, as consumers have a streamlined option to recycle their old Ice Dragon pulse devices after surpassing their product life. The exception to this recyclability lies in the piston material, PTFE. PTFE can be recycled, but loses the majority of its most desirable properties in the process.

Furthermore, facilities with the capability of recycling PTFE are far from plentiful. However, the pistons and cylinder account for less than 15% of the entire pulse device's volume, so the majority of the product is recyclable. For consumers who wish to recycle their old pulse devices, the most efficient recommendation for recycling is to remove and discard the PTFE pistons and cylinder and then recycle the remainder of the device.

More important than recycling old products is reducing the amount of material utilized in the initial manufacturing. The environmental impact equation is:

$$Impact = Population * Affluence * Technology \quad \text{Eq. 17}$$

This equation shows that environmental impacts of a product can be reduced by reducing the impact per unit of resource. Options for minimizing the volume of ABS filament used include designing thinner walls and carving out unnecessary volume which does not actively support the structure of the device. The walls of the device need to be thick enough to sustain the pressures within, but overusing plastic is a waste of material. Additionally, there may be regions of the device which are filled with plastic where it is not benefitting the structure significantly. For example, there may be sharp or squared edges on the design where less material is used for a rounded/edgeless design. There may also be interior sections which are filled with ABS that support the structure just as well if they were not filled.

The use of PTFE poses a problem to the recyclability of the overall product. Since PTFE loses most of its properties after recycling, the discarding of waste PTFE during manufacturing is essentially limited to the landfill. However, waste can still be reduced by applying the

implications of Equation 17. The process of machining the pistons from the PTFE sheets is made for the reduction of materials and environmental effects. By focusing on the orientations of the cuts, the waste material can be minimized and less PTFE will be sent to the landfill as a consequence of manufacturing, reducing the effect of PTFE's recyclability problem. The objective of these material reductions is not to minimize cost, because the cost of ABS and PTFE are already low. Rather, it is to account for the devices which will go un-recycled at the end of their lives, and to minimize the use of virgin plastics. The non-plastic aspects of the pulse device can also be considered with the environment in mind. Fasteners allow for modular design, and are an important part of the product to leave accessible to the consumer. Fasteners are necessary for mounting the device to the inside of the consumer's computer. If a consumer misplaces or breaks a screw, it needs to be easily replaced. The best way to ensure easy replacement is by adhering to standard screw sizes, which can be found in most hardware stores.

The pulse device product is intended to be eventually packaged and shipped to consumers. For this reason, it is important to consider packaging materials and design. With respect to costs, it is cheapest to use traditional packaging materials such as polystyrene foam and cardboard. While cardboard takes two months to decompose in a landfill, and can otherwise be easily recycled at most metropolitan recycling centers, polystyrene foam does not biodegrade at all, and cannot be recycled. A new alternative for packaging today is mycelium-based, which is a material made of mushrooms. Mycelium-based packaging products are completely biological and self-assembling. At the same time, they are easy to disassemble and will decompose after being discarded. They are as protective as polystyrene foams and certainly more expensive, but much more environmentally-friendly.

### **7.1.5 Design for Ergonomics**

An Ergonomic assessment is important when designing a product because the product needs to be easily accessible and usable by the consumer. The pulse device will be easy to handle as the internals are integrated as a unit and are put together in an enclosure. The bottom of the pulse device is made with holes that can mount directly on the cooling block and can easily be screwed in. The pulse device operates from a motor that operates under the same frequency as the pump, which require no additional human input. The user can easily attach the pump onto the pulse device.

### **7.1.6 Design for Durability**

ABS was used for the 3D-printing of the parts. It was used due to its impact resistance, structural strength and stiffness. It also has a suitable high and low temperature performance, which is good for the pulse device's purpose of heat transfer and constant change of fluid temperature. ABS' insulative properties are favorable especially when dealing with fluids close to electrical components. The cylinder was machined from PTFE that has a low friction factor, which is important due to constant linear movement of the pistons inside the cylinder. The piston was machined out of steel so that the square o-rings fit on tightly and the entire piston sub-assembly fit in the holes of the cylinder. The rotating disk and pistons are designed in order to have the same life span as the pump.

### **7.1.7 Design for Assembly**

Design for the assembly of the product is important due to the fluid within the device. There can be no allowable leakages, because this will result in failure of the mechanical components or even damage to the computer itself. Most of the design will be 3D-printed using ABS with the exception of the pistons and cylinder which will be machined from PTFE and steel respectively. The pulse device will be completely enclosed in such a way that the top part which houses the mechanical components remains dry. These components are a motor and an attached rotating disk. The difference between the design of the pump and the design of the rotating disk is the bottom, which has grooves extruded out to make contact with the pistons upon rotation. This contact with the pistons causes continual oscillatory vertical motion which moves the fluid beneath it. The springs attached to the bottom of the cavity contact the pistons and cause the pistons to return to their original location after being pushed down by the rotating disk. The bottom part of the pulse device located underneath the pistons houses a cavity where the fluid enters and exits through jets. This is the only section of the device which interacts with the cooling fluid, as this is where the heat transfer is intended to take place. The housing components inside and outside of the pulse device will be fastened together using snap-fit. The exterior of the bottom part of the pulse device will consist of holes for screw-fastening to the cooling block. Depending on the consumer's needs, a pump can be pre-placed and attached onto the top of the pulse device or the pump can be attached at a later time by the consumer. As both a modular and integrated system, this design can be assembled to satisfy these two different consumers' needs.

## **7.2 Build Instructions**

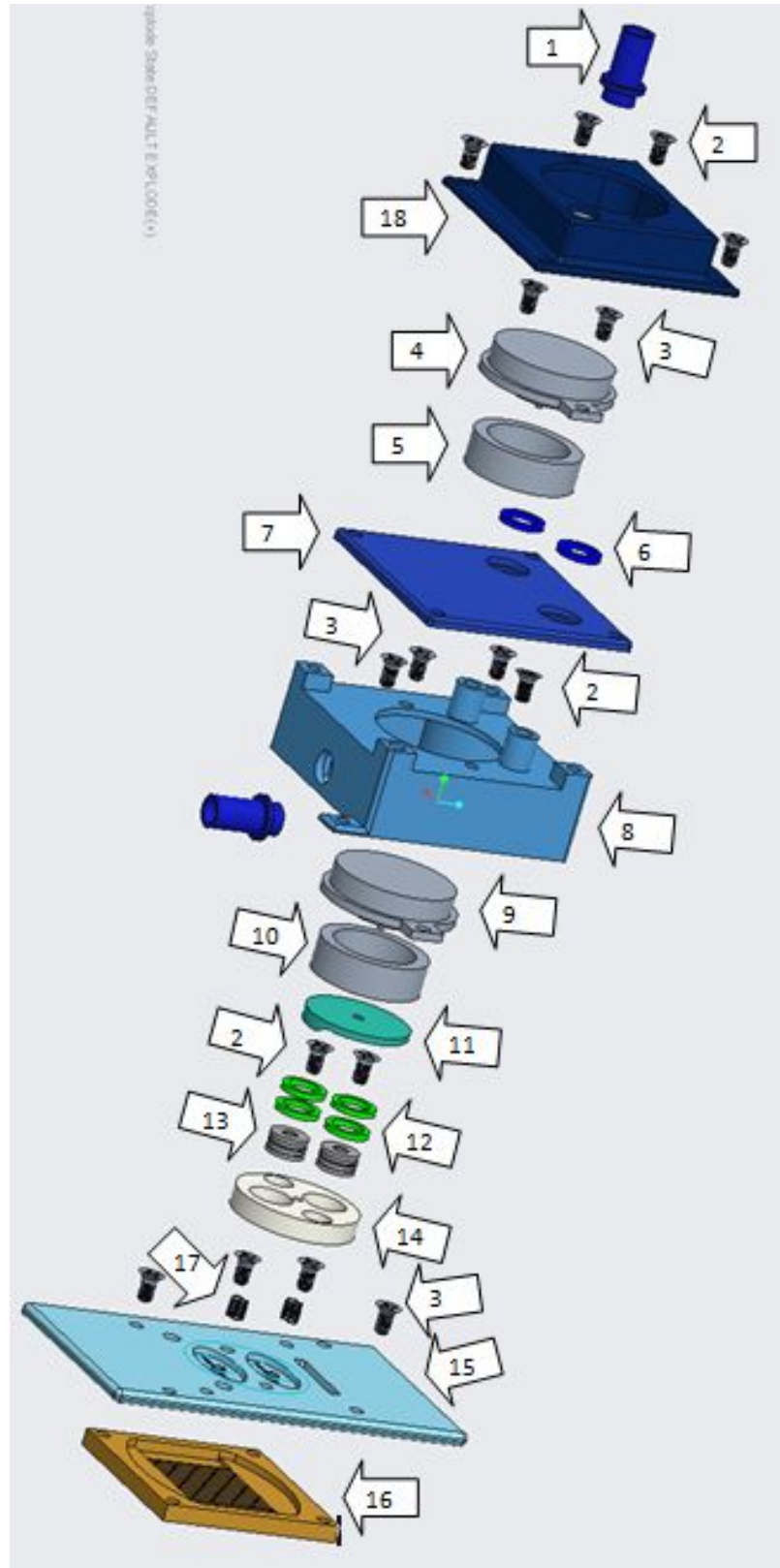
### **7.2.1 Introduction of the Build Instructions**

The pulse device was designed to be an integrated system, meaning once it is put together, it is intended to stay together and not be taken apart. Due to the complexity of the design, it needs to be built in a very specific way so that it runs correctly and does not leak. The part that runs the water through the system, or the pump part, is included in the build instructions but it not necessary to run the pulse device as it is a modular piece and can be replaced by any pump. The exploded view of the design has the parts labelled and is to be used for assembly of the pulse device. Figure 7.4 shows the entire assembled device for reference.

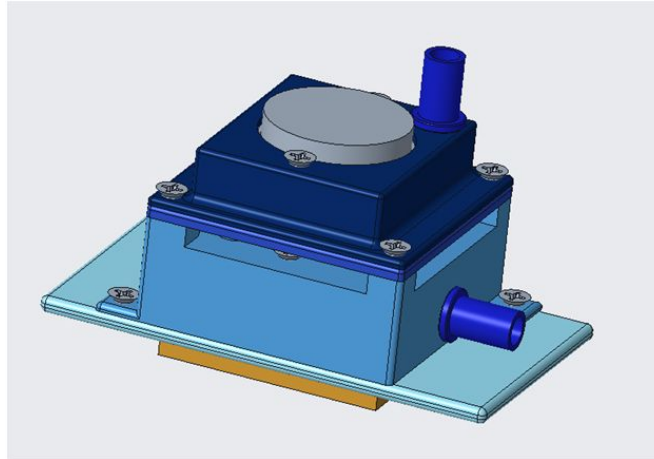
A legend for Figure 7.3:

1. Hose Fitting
2. Sealant Screws
3. Screws
4. 2600 Motor
5. Pump With Impellers
6. O-Rings
7. Enclosure B
8. Enclosure A
9. 3600 Motor
10. Pump Without Impellers
11. Rotating Disk
12. Square O-Rings
13. Pistons
14. Cylinder
15. Jet Block
16. Cooling Block
17. Springs
18. Enclosure C





**Figure 7.3.** Exploded View of Design



**Figure 7.4.** Assembled Product

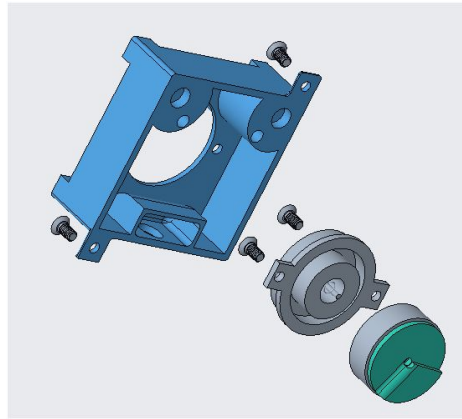
### **7.2.2 Fabrication**

The main process that was used for the prototyping phase was 3D printing. The parts were printed using Fused Filament Fabrication (FFF) with ABS plastic. The design portion for the printing was performed using the Computer Aided Design (CAD) software, Creo Parametric 6.0. This CAD was used to model the parts and then was sliced and converted to an STL file for the 3D printer to read. The parts were printed individually so that they can be assembled together as needed, so the parts were each oriented to minimize waste material. The 3D printer has a filament diameter of 1.75 mm and a nozzle diameter of 0.4 mm, which allows for high tolerance as the design requires.

## New parts needed:

### 1. Rotating Disk

- a. Magnetism is the driving force to obtain rotational motion of the disk, therefore the motor and impeller of an Alphacool DC-LT 3600 pump were utilized. The impeller blades of the 3600 pump were grinded down so that only the base of the impeller remained. To replace the blades, the top of the rotating disk was 3D printed and epoxied to the base of the impeller. See Figure 7.5.



**Figure 7.5.** Exploded Rotating Disk View

### 2. Cylinder

- a. The PTFE (Teflon) rod was cut to size with a saw to create the cylinder. Once to the correct height, a drilling machine was used to shape the holes in the cylinder to the appropriate dimensions.
- b. This part is a solid cylinder piece with two holes extruded through the top and two counterbored screw holes on opposite sides of the cylinder. This is the central working system for the reciprocating pistons.

### 3. Pistons

- a. An angle grinder was used to cut the pistons out of the rod and a lathe was used to create the grooves in the two pistons.
- b. This part is a pair of pistons that will be the moving component contained by the cylinder and made gas-tight by two square profile o-rings ( $\frac{1}{2}$ " OD  $\frac{3}{8}$ " ID). The two pistons were machined out of a 0.5 inch diameter steel rod, with a lathe that created two grooves in each piston for the o-rings. A lathe ensured a smooth finish to allow for minimal friction when placed in the cylinder.

### 4. Jet Block

- a. FFF was used to create the jets block.
- b. This part is a solid block with multiple holes extruded out, so it is a simple design to print. The small holes at the bottom of the large cavities shown in Figure 7.3. For this reason, the part will be oriented with the hole/jet-side on the bottom. This orientation will create zero waste material to be taken off after the printing

### 5. Enclosure for Pulse Device

- a. The FFF process were used to create the enclosure.
- b. This part is a box with two holes extruded out- one being circular and one being rectangular. Due to the holes coming out the bottom, this part will be printed upside-down, compared to the orientation shown in Figures 7.3 and 7.4. This means that the "top" of the box will be printed first and the FFF process will build the walls from the bottom up. This orientation will allow for zero waste of the ABS.

### 7.2.3 Assembly Instructions

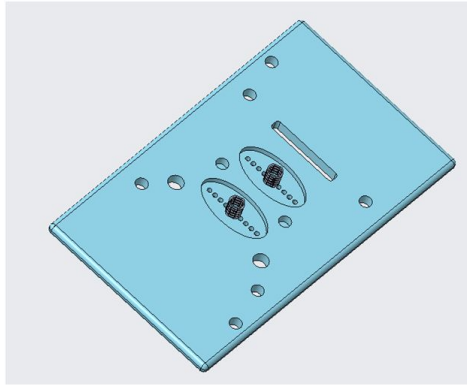
Table 7.1. Assembly Part List

Part #	Description	Material	Source	Quantity
1	Hose Fittings	ABS	MatterHackers	2
2	Sealant Screws	M4 x 0.7 mm Thread Size, 8 mm	McMaster-Carr	6
3	Screws	A2/18-8/304 Stainless Steel	Lowe's Home Improvement Store	10
4	2600 DC Motor	Various	AlphaCool	1
5	Pump With Impellers	Ferrite	Donation	1
6	O-Rings	Rubber	McMaster-Carr	2
7	Enclosure B	ABS	MatterHackers	1
8	Enclosure A	ABS	MatterHackers	1
9	3600 DC Motor	Various	AlphaCool	1
10	Pump Without Impellers	Ferrite	Donation	1
11	Rotating Disk	ABS	MatterHackers	1
12	Square O-Rings	Rubber	McMaster-Carr	4
13	Pistons	Steel	Lowe's Home Improvement Store	2
14	Cylinder	PTFE	McMaster-Carr	1
15	Jet Block	ABS	MatterHackers	1
16	Copper Cooling Block	Copper	Donation	1
17	Spring	Metal	McMaster-Carr	2
18	Enclosure C	ABS	MatterHackers	1
19	Cooling Block Sealant	Rubber	Donation	1

## **Assembly:**

### **Subassemblies:**

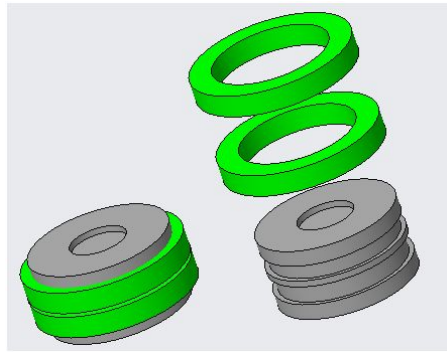
#### **1. Subassembly 1: Jet Block**



**Figure 7.6.** Jet Block Subassembly

- a. Need: jet block (15), sealant ring (18), 2 springs (17), epoxy
- b. Place jet block (15) with flat side up
- c. Place cooling block sealant ring (18) in corresponding crevice. Ensure that all corners are aligned
- d. Flip jet block (15) so that flat side faces down
- e. Place one end of a spring (17) around circular extrusion in one oval cutout in jet block (15). Silicone or epoxy may be added to base of spring if necessary to keep spring (17) in place
- f. Repeat step (1e) for second spring (17)

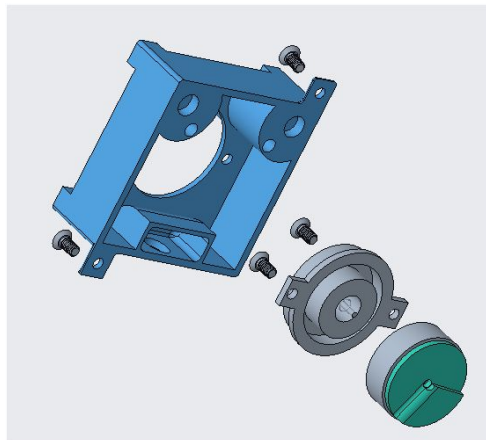
## 2. Subassembly 2: Pistons



**Figure 7.7.** Piston Subassembly

- a. Need: 2 Pistons (13) and 4 Square O-rings (12)
- b. Place two square O-rings (12) around grooves in one piston (13)
- c. Repeat step (2b) for second piston

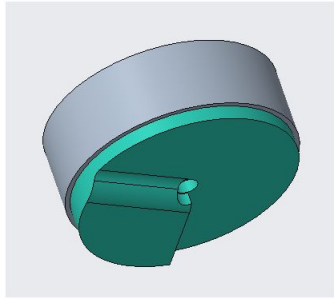
## 3. Subassembly 3: Enclosure A



**Figure 7.8.** Enclosure A Subassembly

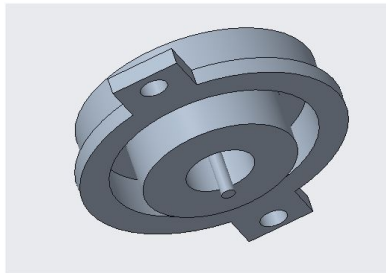
- a. Need: Enclosure A (8), 3600 DC motor (9), rotating disk (11), pump without impellers (10), 2 sealant screws (2)

- b. Epoxy rotating disk (11) onto pump (10). See Figure 7.9.



**Figure 7.9.** Rotating Disk Epoxied to Pump

- c. Place motor (9) with label facing down. See Figure 7.10.

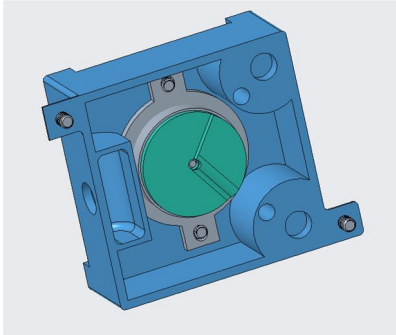


**Figure 7.10.** Motor Facing Down. *Note center shaft.*

- d. Hold rotating disk (11) with blade side facing up
- e. Insert rotating disk (11) into white shaft of motor (9). There should be a magnetic pull during insertion
- f. Insert female end of motor cord (9) through large circular hole through bottom hole of enclosure (8) until tabs on motor (9) are flush with the enclosure (8)
- g. Align screw holes on motor (9) and enclosure (8)
- h. Flip current subassembly 3 so top side faces up. Hold parts together so motor tabs (9) remain flush with enclosure (8)

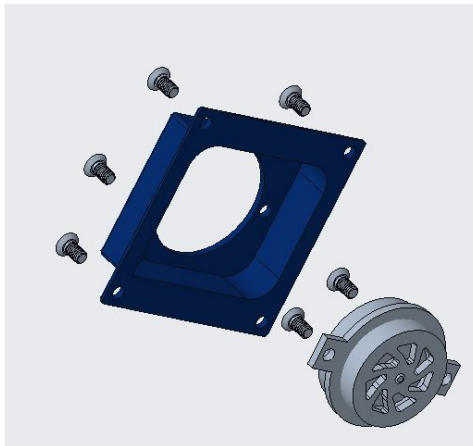


- i. Screw enclosure to motor tabs (9) with 2 sealant screws (2). The screws (2) will have heads facing up on top of enclosure (8). See Figure 7.11



**Figure 7.11.** Inside of Enclosure A

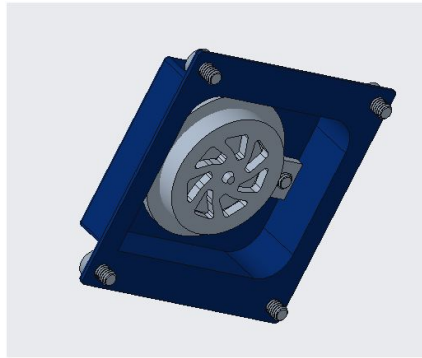
#### 4. Subassembly 4: Enclosure C



**Figure 7.12.** Enclosure C Subassembly

- a. Need: Enclosure C (18), 2600 motor (4), and pump with impellers (5)
- b. Insert female end of motor cord (4) through large circular hole through bottom hole of enclosure (18) until tabs on motor (4) are flush with the enclosure (18)
- c. Align screw holes on motor (4) and enclosure C (18)

- d. Flip subassembly 4 so top side faces up. Hold parts together so motor tabs (4) remain flush with enclosure (18)
- e. Screw enclosure (18) to motor tabs (4) with 2 sealant screws (2). The screws (2) will have heads facing up on top of enclosure (18). See Figure 7.13.

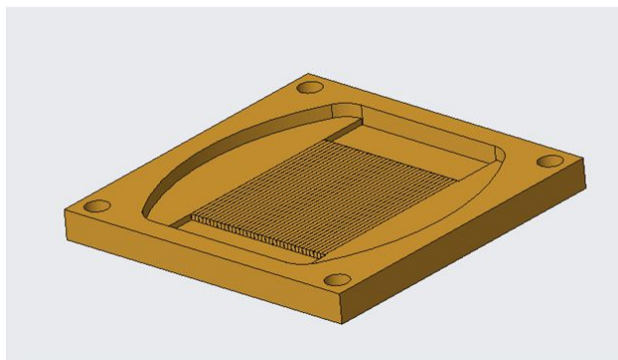


**Figure 7.13.** Inside of Enclosure C

Main Assembly:

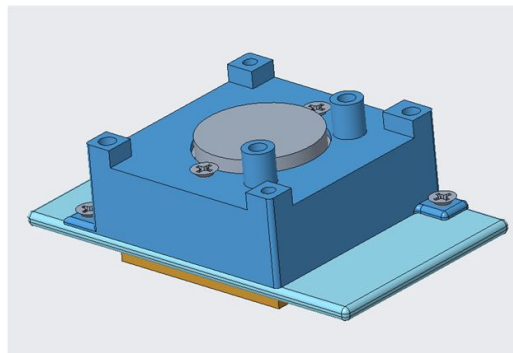
5. Orient copper cooling block (16) with flat side down and microchannels facing upward.

Microchannels should be oriented horizontally. See Figure 7.14.



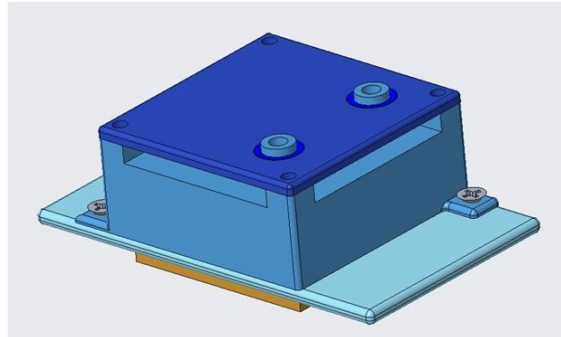
**Figure 7.14.** Copper Cooling Block

6. Hold Subassembly 1 so that long slit on jet block (15) is on right side and spring side faces up. Ensure that cooling block's (16) four corner holes are aligned with corresponding holes on jet block (15)
7. Screw jet block (15) to cooling block (16) using four 8mm screws (3). Have screw heads on the jet block (15) side and ends through the cooling block (16) side
8. Place cylinder (14) onto center of jet block (15) with center shaft hole facing up. Align two counterbored screw holes (14) with corresponding holes in jet block (15)
9. Hold one assembled piston (Subassembly 2) with spring groove facing down. Place piston (Subassembly 2) into one large cylinder hole (14) so that end of spring (17) fits into piston's spring groove (13)
10. Repeat step 9 for the second assembled piston (Subassembly 2)
11. Place Subassembly 3 onto jet block (15) so that tabs (Subassembly 3) align with screw holes (15) and so that the outlet hole (8) is oriented to the right. **Important: The outlet hole (8) should be on the same side as the long slit in the jet block (15)**
12. Screw Subassembly 3 to jet block (15) using two 6mm screws (2). See Figure 7.15.



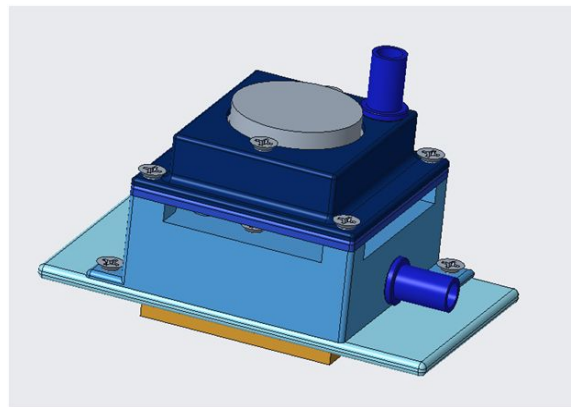
**Figure 7.15.** Subassemblies 1, 2 and 3

13. Hold Enclosure B (7) with grooves facing up. Place Enclosure B (7) onto Subassembly 3 so that cylinders (8) align and snap-fit. See Figure 7.16.



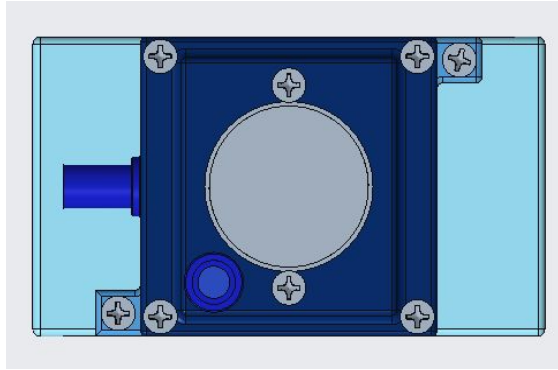
**Figure 7.16.** Enclosure B on Subassembly 3

14. Place one orange O-Ring (6) into a groove on Enclosure B (7)
15. Repeat Step 14 with another O-Ring (6) and the other groove on Enclosure B (7)
16. Place Subassembly 4 onto Enclosure B (7), aligning holes. See Figure 7.17 for orientation



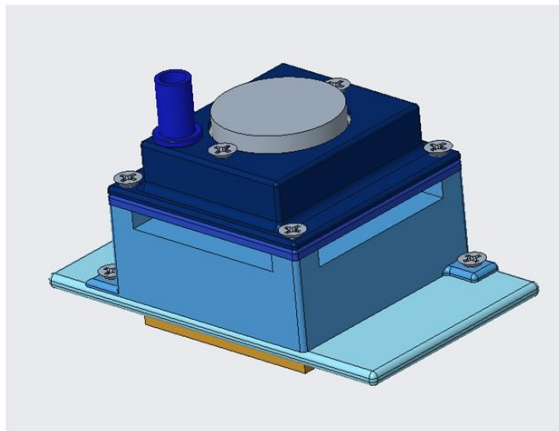
**Figure 7.17.** Entire Assembly

17. Screw Enclosure C (18) and Enclosure B (7) to Enclosure A (8) using four sealant screws (2) by aligning holes. See Figure 7.18.



**Figure 7.18.** Top View of Design

18. Insert smaller side of hose fitting (1) into inlet hole of Enclosure A (8)
19. Insert smaller side of hose fitting (1) into outlet hole of Enclosure A (8)
20. See Figure 7.19 for final design.



**Figure 7.19.** Final Assembly, Alternate View

## **8. Product Cost/Economic Analysis**

### **8.1 Introduction**

An economic analysis is important in product design due to the many implications associated with costs including product value, associated costs, and benefits/savings/revenues. These values are useful in determining the scope of the product's economic potential. An analysis of the breakeven point, net present worth, and internal rate of return can guide the development and future of the product in terms of investment and future economic opportunities.

### **8.2 Product Value**

The goal for this product was to create turbulent flow in a CPU cooling device which increases the efficiency of heat transfer in the system. Increasing the rate of heat transfer decreases the energy usage to run the system, or the power usage to run the device. The goal was to save power usage by 10% as turbulent flow has a much higher heat transfer rate than laminar flow. Personal computers used by the general public do not use an extensive amount of energy, so the main cost savings will be achieved by integrating the pulse devices in server farms which house thousands to millions of servers that run all hours of the day. A typical CPU cooling device costs \$149/year to run in a server farm. As an example, Facebook's main server farm holds about 30,000 servers, and it costs about \$4,470,000/year to run the CPU cooling devices. If 10% savings were made from the new pulse device system, then Facebook's server farm saves \$447,000/year, or \$37,250/month, or \$1,201/day. Alternatively considering a smaller scale, this pulse device saves the average computer user about \$15/year.

### 8.3 Associated Costs

The material cost of the proposed prototype was based on the bill of materials for the prototype. These materials were separated into three components: the power source, pulse device, and supporting accessories. A full breakdown of the components is detailed in Table 1.

Table 1. Material Cost of Prototype

Component	Description	Costs	Total Cost
Power Source	DC Motors	\$50	\$50
Pulse Device	Rotating Disk	\$0.19	\$92.54
	Enclosure	\$0.15	
	Jet Block	\$0.20	
	Copper Cooling Block	\$0.00 ( <i>donation</i> )	
	Cylinder	\$92	
	Pistons		
Supporting Accessories	Screws	\$11.48	\$36.16
	O-Rings	\$3.74	
	Spring	\$7.99	
	Required Maintenance Accessories	\$12.95	
<b>Total</b>			<b>\$178.70</b>

As referenced in Table 1, most of the cost associated with the project was derived from the pulse device due to the out-of-house machining of the recycled Teflon. While the Teflon material is relatively cheap, the estimated labor costs encompass the bulk of the total cost. The labor costs were calculated based on the time approximation of 2 hours (an assumed hourly rate

of \$35/hour at the University of South Carolina's Machine Shop) to machine the Teflon. Aside from the manufacturing of Teflon, the 3D printing of the other parts were completed in-house using ABS, a very low-cost filament.

Another cost associated with the project was Dr. McCants' time. As head of research and development, Dr. McCants' time is money taken away from other aspects of the company. It was assumed that Dr. McCants spent approximately one hour per week for meetings, transportation of materials, and additional support in development. This assumption along with an arbitrary rate selected based on similar salaries totals \$1800 for the Fall '18-Spring '19 school year.

A large portion of manufacturing costs and testing costs were eliminated due to donations. The 3D printer used to manufacture a large portion of the pulse device is Dr. McCants' personal printer so there was no need to out-source for either labor or manufacturing. The testing rig was also provided by the sponsor from existing lab materials and only required minor maintenance fees as referenced in Table 1. The copper cooling block was also donated by Dr. McCants and was used as the primary block for all prototyping activities.

New users must understand how to use the 3D printer. Therefore, a portion of filament was used for initial familiarization of the printer. To ensure that the prototype design was printed with no complications, practice trials were performed to acquire the basic 3D printing skills such as software knowledge, correct bed and nozzle temperature, leveling and proper orientation, and printing speed. Once this was complete, a more precise set of instructions was compiled for future use. This improved printing efficiency and anticipated canceling trial filament costs for future prototypes. Therefore, a larger investment in training at the time yielded a positive payback in the long run.



The total initial cost value is \$3,660.60 which includes manufacturing fees, materials, sponsor time, and a burden of 85% to account for any missing fees. After the initial cost, each device will cost \$153.70. This cost can eventually be reduced as device improvements are made.

#### **8.4 Benefits/Savings/Revenues**

The primary benefits associated with this project are the customer's financial savings. These are achieved through using the product's efficiency by using less energy to achieve lower CPU temperature levels. This reduction in energy is caused by the increased heat transfer of the CPU, which leads to savings of \$447,000 per year in the server farm example explained in Section 8.1. An increased market share will result due to the decreased operating costs in energy, a goal toward which all companies strive.

For a large company's server farm that houses thousands to millions of servers, there is a high demand for lower energy costs. The goal of the device is to save the customer 10% in costs. A typical CPU cooling device will cost \$149/year to run in a server farm which amounts to about \$4,470,000/year to run on a server farm with 30,000 servers. For 10% cost savings for the server farm scenario, \$37,250/month or \$447,000/year are achieved.

Due to a majority of the product being 3D-printed, manufacturing costs were already low. Use of the sponsor's personal 3D printer saved in development and labor costs associated with the manufacturing of the product. A test rig was also provided which further saves in testing costs. As the design and printing process are refined in the future, manufacturing and assembly costs will be further reduced.

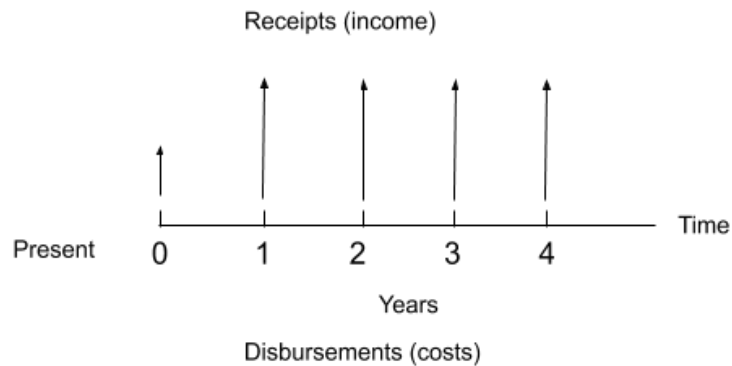
## 8.5 Suggested Approaches

A Cash Flow diagram was used to demonstrate the net change in funds of a project or company over time. At the time, the costs out-weighed the income, because the device was in the design and development phase. Disbursements were greater than receipts because initial materials and tooling were being supplied, and hours of labor were being devoted to production before profit was generated. However, the coming years are projected to not only replace but surpass the expenditures of Year 0.

The starting costs for Year 0 were calculated to be \$3,660.60. The calculated cost for outputting one product is \$153.70, a value obtained from the Bill of Materials. In order to make a profit, the simplest approach to pricing an item is to double the wholesale price. This results in a retail price of \$307.40. One scenario assumes that one server farm per year is supplied with new pulse devices, and each server farm has 30,000 servers which each requiring one pulse device. The revenue for this scenario was calculated to be \$9,222,000. The Cash Flow Diagram for this scenario is shown in Figure 1. Alternatively, it is assumed that 300 pulse devices are sold to individual users every year, the revenue amounts to \$92,220 per year. The Cash Flow Diagram for this scenario is shown in Figure 2.



**Figure 8.1.** Cash Flow Diagram: Server Farm Scenario



**Figure 8.2.** Cash Flow Diagram: Individual Buyer Scenario

With these calculations, the breakeven point in the production could be determined. For the server-farm scenario, the expenditures in Year 0 are \$3,660.60 plus \$4,611,000 and the revenue is \$9,222,000. Each year following, the expenditures are \$4,611,000 and the revenue is \$9,222,000. This gives a net profit of \$4,611,000 per year following Year 0. Therefore, the breakeven point occurs early in the first year.

For the individual purchaser scenario, the expenditures in Year 0 are \$3,660.60 plus \$46,110 and the revenue is \$92,220. Each year following, the expenditures are \$46,110 and the revenue is \$92,220. This gives a net profit of \$46,110 per year following Year 0. Therefore, the breakeven point also occurs early in the first year.

Net Present Worth (NPW) focuses on the present financial situation of a project. It is the difference between the project's benefits and costs. This was demonstrated for the current year and also projected for the future in a Cash Flow Diagram. Ideally, NPW is computed before determining the final design to be implemented, so that the NPW's of several designs can be compared. In this way, the design with the greatest positive value for NPW can be selected to be

pursued. A positive NPW value implies that the projected earnings of a project exceed the anticipated costs. An investment with a positive NPW value is assumed to result in profits, and therefore only investments with positive NPW values are worth considering when deciding upon a project. NPW is calculated using Equation 18:

$$NPW = \text{present worth of benefits} - \text{present worth of costs} \quad \text{Eq. 18}$$

The present worth of benefits is the sum of future revenues converted to the present value over the lifespan of the project. For a five-year projection, the benefits appear to be excellent. Considering the low-end approximation, where 300 devices are sold individually to consumers, this product could profit \$46,110. However, many resources (time, material, work) were invested in the project, so the present worth of costs is high. This value is calculated to be approximately \$3,660.60. Thus, the NPW of the project is computed as \$42,449.40.

The Internal Rate of Return (IRR) is used to determine the interest rate which results in equivalency of the present and future sums, or the NPW equal to zero. The lifespan of a single product is assumed to be approximately 65,000 hours. IRR is calculated using Equation 19:

$$0 = NPW = \sum_{n=0}^N \frac{CF_n}{(1 + IRR)^n} \quad \text{Eq. 19}$$

$CF_n$  = Cash Flow per Period  
 $n$  = Each Period  
 $N$  = Holding Period  
 $NPW$  = Net Present Worth  
 $IRR$  = Internal Rate of Return

For the project, one period was assumed to be equivalent to one year, and the holding period was assumed to be the end of the fourth year of production. The Cash Flow for the server-farm scenario amounts to \$600,000/year. Using Equation 19, the IRR for this scenario was computed to be 16390.756%. The Cash Flow for the individual-buyer scenario amounts to \$6,000/year. Using Equation 19, the IRR for this scenario was computed to be 160.399%.

## **8.6 Summary**

The product value was determined to yield savings of \$447,000/year based on the \$149/year cost to run in a server farm. The total initial cost value is \$3,660.60 which included manufacturing fees, materials, sponsor time, and a burden of 85% to account for any missing fees. After the initial cost, each device will cost \$153.70. For the server-farm scenario analyzing the breakeven point, the expenditures in Year 0 are \$3,660.60 plus \$4,611,000 for production of 30,000 devices, and the revenue is \$9,222,000. Each year following, the expenditures are \$4,611,000 and the revenue is \$9,222,000 which gives a net profit of \$4,611,000 per year. The Net Present Worth of the project was found to be \$42,449.40. Using the cash flow for the server-farm scenario of \$600,000/year, the Internal Rate of Return for this scenario was computed to be 16,390.756%. These numbers are contingent on a properly-functioning device that meets all specified needs, but present extremely favorable returns.

## **9. Testing**

### **9.1 Introduction**

Rapid prototyping is followed by testing the device against the product specifications. Testing allows for refinement, determining issues, fixing the issues, and then retesting multiple times until the device is as successful as possible. The equipment, testing process, and each detailed test plan are detailed below.

### **9.2 Test Equipment**

A test rig for the pulse device and cooling block was provided by the industry sponsor. This test rig allows for controlled tests prior to and after the implementation of the device, with various components to properly test the specifications of the design. The test rig consists of a radiator with input and output tubing, thermocouple and flowmeter data acquisition systems, and water as the working fluid within the enclosed device. LabView programs are utilized to obtain and analyze the data.

#### **Radiator Closed Loop System**

The test rig setup is constructed in a plexiglas frame, with an AlphaCool NexXxoS XT45 Full Copper Radiator mounted to the adjacent hinged wall.  $\frac{3}{8}$  inch inner diameter -  $\frac{1}{2}$  inch outer diameter - clear nylon tubing were cut into 1 foot pieces in order to reach the inlet and outlets of the pulse device. The tubing is clamped to the input and output of the radiator, sealed by tube fittings on each inlet. A fan is mounted on the front of the radiator for cooling, and connected to a power source.

## **Thermocouple and Flowmeter**

Thermocouples used for testing were K-type, PFA insulated thermocouples from Omega Engineering model number 5TC-TT-K-40-36. These thermocouples were relatively small and were placed at four different locations on the test rig. Two thermocouples were bent at the tip so they protrude halfway into the flow of the tubes of the radiator, one ambient thermocouple is placed above the radiator, and one is inserted into the copper cooling block itself.

The flow meter used for testing is a Koolance Coolant flow meter, which is used to measure the flow rate of the fluid leaving the cooling block back to the radiator. Both the thermocouple and flowmeter systems are powered by a power source connected using various electrical routes. Readings are recorded using two separate DAQ cards, National instruments USB-9162 and USB-6009. The data is then analyzed using Labview and excel.

## **9.3 Testing Process**

Prior to testing, the device will be checked for leaks by running water through the inlet tubing. Any leaks that occur within the system will be altered with silicone and o-ring adjustment until proven watertight. The cooling block will start at a constant temperature as heat is needed to measure the heat transfer of the system. The device will be tested first without pulses and then with 5 different frequencies. The temperatures are then recorded and the heat transfer can be calculated. The flow rate is also tested under different frequencies to find the optimal speed at which the motor is to run for maximum heat transfer. The device will be tested for durability by running for extensive periods of time. It will run continuously in order to be analyzed according to its longevity and proper operation.

## 9.4 Test Matrix

The test matrix shown in table 9.1 is a visual representation of each experiment performed. The columns serve as the independent variables A, B, and C. Variable A is the inlet temperature, variable B is the varying frequency, and variable C is the flow rate. The output variable tested is the outlet temperature, to determine the heat transfer of a full cycle. It was concluded from the matrix that 7 trials were to be performed to analyze and interpret the data.

Table 9.1 Test Matrix

Factor and Factor Level				
Trial no.	A	B	C	Outlet Temp
1	1	1	1	**
2	1	2	1	**
3	1	1	2	**
4	2	1	1	**
5	2	1	2	**
6	2	2	1	**
7	2	2	2	**

## 9.5 CPU Liquid Cooling System Without Pulses

In order to assess the effects of the pulse device on the system, the original system will first be tested, serving as a control experiment. The original system consists of a radiator with outlet tubing that connects to a pump and then a cooling block which rests on a CPU. The outlet tube from the cooling block returns the fluid to the radiator. The circulated fluid should ideally be one with the highest possible heat transfer coefficient, but for the purposes of a control



experiment with an average coolant, water will be used. To avoid employing the pulse device, the motor will not be run by simply disconnecting it from power. The results of this test will display the heat transfer achieved across the cooling block for a laminar flow. By conducting the following tests, efficiency and heat transfer improvements will become apparent.

## **9.6 Pulse Device at Varying Frequencies**

By design, the CPU liquid cooling device will accommodate a variety of computer systems and have a high heat transfer rate at varying frequencies transmitted from the pump signal. This adaptability allows consistent cooling within one computer unit regardless of the stress placed on the system. To test the varying frequencies, tubing will connect the outlet of the device to a flowmeter, and the flowmeter to the inlet of the radiator. A LabView program is used to collect and analyze the flow rates, displaying an output of a square wave. A square wave is a non-sinusoidal periodic waveform that represent the pulse values throughout the experiment.

For the test, 7 trials will be performed at varying frequencies, each value selected based on motor specifications. The results of these trials will help determine the pulse device's efficiency in relation to power, whereas the pulse device will be more efficient if the frequency increases at a slower rate than its power consumption.

## **9.7 Pulse Device Efficiency Based on Temperature**

The most important parameter to test is the temperature of the CPU for heat transfer analysis and efficiency of the design. An increase in the heat transfer rate is defined as an increase in the temperature difference between the fluid entering and the fluid exiting the cooling

block (which is in direct contact with the CPU). Thermocouples connected to Labview will be used to measure the temperatures of the CPU, inlet, outlet, and ambient air. The CPU will be set at a required temperature as heat is needed to measure the heat transfer of the system. As portrayed by the test matrix, 7 trials are to be performed to analyze and interpret the data of this experiment. The recorded temperatures will be used to calculate the heat transfer, and the efficiency of the pulse device can then be deduced based on the power required to run in relation to the heat transfer accomplished.

## **9.8 Conclusions**

The results of the tests performed are correlated to the target design specifications of the pulse device. The flow rate, heat transfer, and frequency were measured and calculated to analyze the functionality and performance of the pulse device. Leakage tests were performed to check for leaks by running water through the inlet tubing which alterations were made to ensure its impermeability. Durability of the design was also tested by running the system for extensive periods of time. In conclusion, the tests performed determined the efficiency of the pulse device. The results of the tests are also a good source of feedback towards future work and improvements of the design.

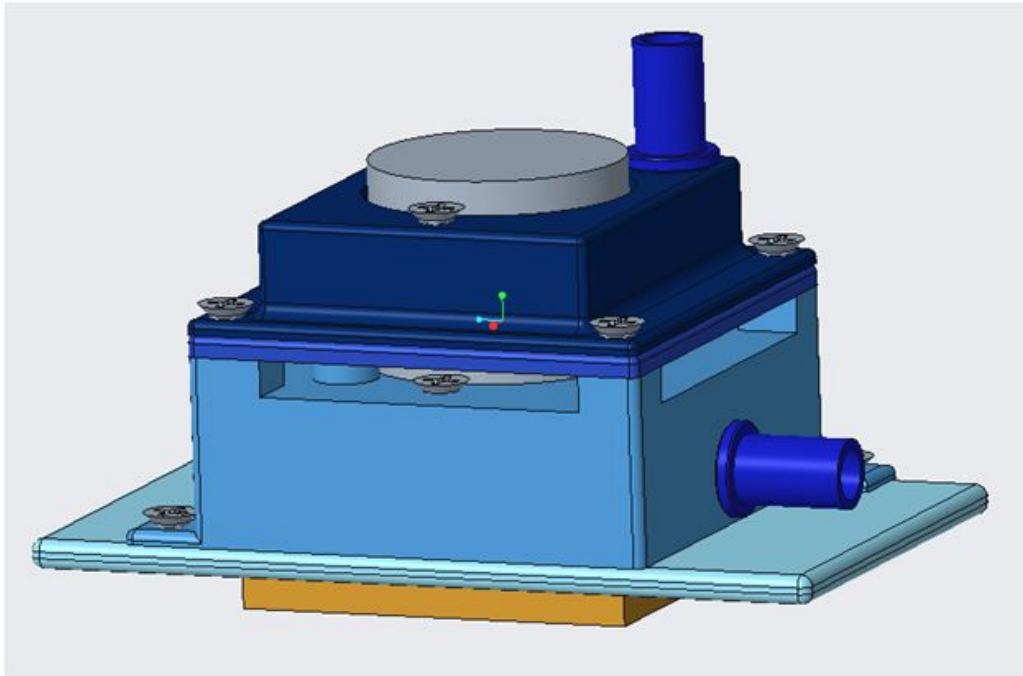
## **10. Final Design/Conclusions on Design Product**

### **10.1 Summary of Designed Product Results**

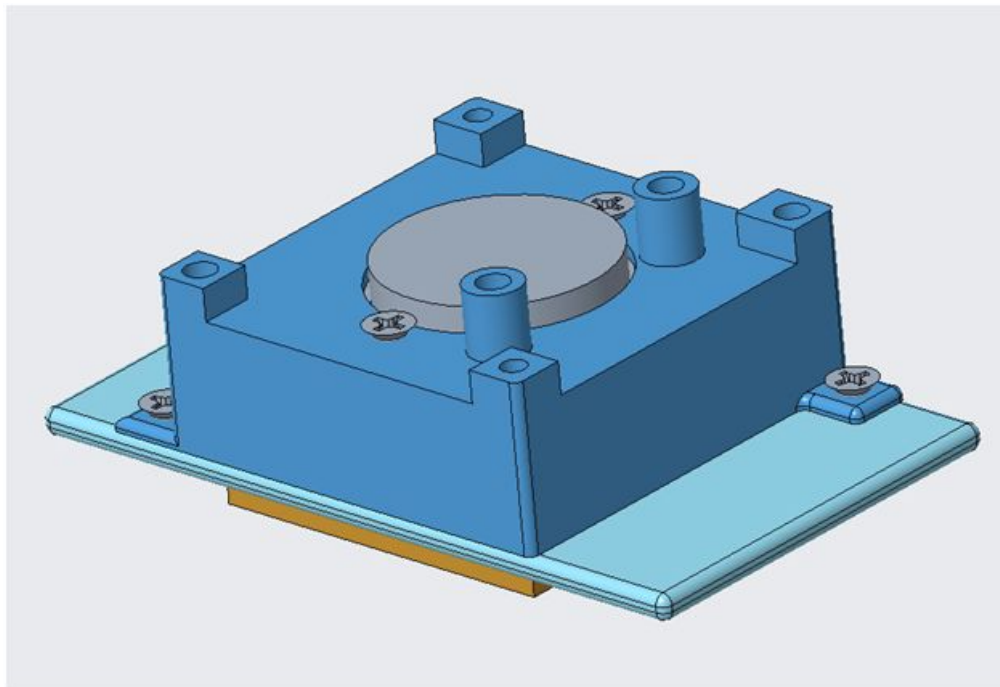
Overall, the concept selected for the CPU liquid cooling pulse device is projected to fit the needs and specifications of the sponsor. All necessary materials have been acquired to conduct the planned tests of the product. Without the prototype tests, the product cannot yet be deemed ready for commercialization. However, the project scope requires a functioning prototype to be delivered to the industry sponsor rather than a final product ready for manufacturing and distribution. Execution of the detailed test plans will be used to confirm the expected functionality of the prototype, which satisfies the sponsor's needs and specifications.

#### **Final Drawings**

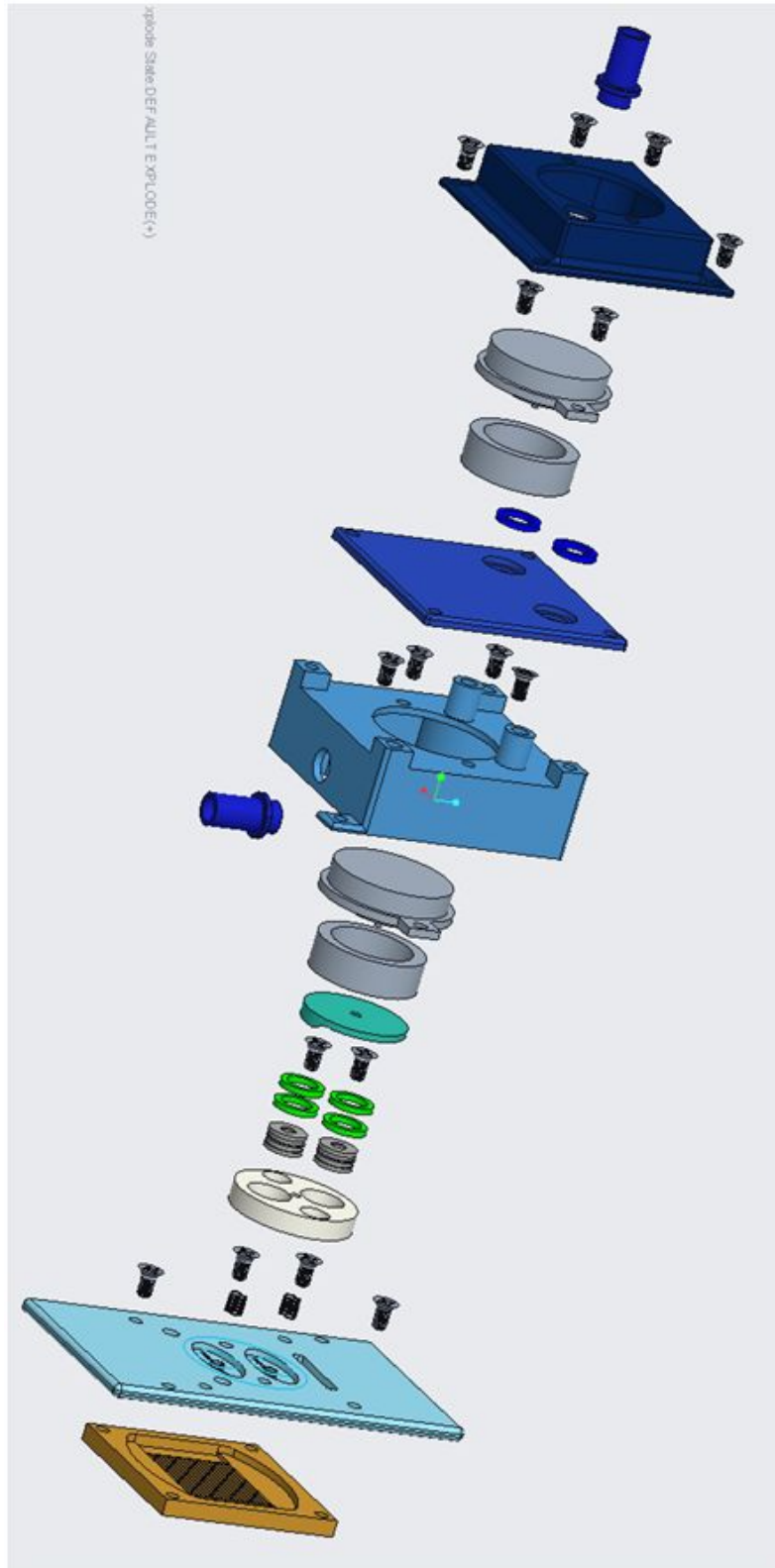
The final concept employs the existing pump to rotate an impeller blade that actuates pistons. The generated pulse from the pistons creates turbulent flow in the water across the cooling block, thereby maximizing heat transfer. The final design has an integrated pulse device system, but a modular pump. The modular pump allows for any pump to be used with the pulse device without changing the design. The pulse and pump designs are shown in Figure 10.1, the pulse device alone in Figure 10.2., and the exploded view of the entire system in Figure 10.3.



**Figure 10.1.** Final Design



**Figure 10.2.** Pulse Device in Enclosure



**Figure 10.3.** Exploded View of Final Design

## Specifications

Table 10.1. Final Metrics Specifications

Metrics	Specifications
Material	ABS
Shape	50,000 mm <sup>3</sup>
Cost	\$269
Ease of Manufacturing	3D Printing
Flow Rate	76 L/h
Radiator Fan Speed	2160 rpm
Pump Speed	2600 rpm
Reynold's Number	4000

## Bill of Materials

*Bill of materials located in Appendix B.*

### Suppliers

- Ice Dragon Cooling
- MatterHackers
- McMaster-Carr
- Ace Hardware
- Lowe's Home Improvement
- Office Depot

## **10.2 Future Product Development**

Changes to certain aspects of the design will improve applicability of the product. Future work on the CPU Cooling Pulse Device will consist of improved sealing and standardization. Sealant can be improved by using a rubber seal with the exact dimensions of the enclosure to seal the water from getting inside of the enclosure containing the pistons, cylinder, rotating disk, and motor. Other sealing can be improved by standardizing the tube fittings at the inlets and outlets of the to ensure CPU cooling market consistency. This will also mean that the fittings will fit perfectly in the holes of the enclosure, which will help sealing. Further testing of the design is also recommended to obtain a more accurate analysis of the results.

## **10.3 Lessons Learned**

The most significant takeaway from the design process is the insight into product development. Some aspects of the design were overlooked early in the design process which resulted in the need for several changes in the later stages of the product development. In hindsight, determining these aspects earlier may have helped in reducing these changes. However, the nature of engineering design is to have multiple iterations of a product that reduce error and achieve the end goals more effectively each time. Therefore, while noticing certain problematic elements earlier in the design process may have expedited production and testing, there will always be some factor of error in design that can only be removed after multiple design iterations.

# Appendices

## Appendix A

### Contacts

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Appendix B

Bill of Materials

Item #	Item Number	Material Description	Purchased	Fabricated	Fabrication	Supplier	Vendor Item #	Units/Pack Qty	Unit Quantity	Material \$/unit	Labor \$/unit hour	Time Devoted (hours)	Item Total Cost
1	DC Motor	Alphacool DC-1T 2600 Ultra low noise ceramic - 12V DC	x			Ice Dragon Cooling	1012576	2600 rpm	1	0	0	0	0
2	DC Motor	Alphacool DC-1T 3600 Ultra low noise ceramic - 12V DC	x			Ice Dragon Cooling	49061	3600 rpm	1	0	0	0	0
3	Rotating Disk	Red MH Build Series ABS Filament - 1.75mm (1kg)	x	x	Ice Dragon Cooling	MatterHackers	MS3MQJT1	1kg Spools	1	19.99	0	1	19.99
4	Enclosure for Pulse Device	White MH Build Series ABS Filament - 1.75mm (1kg)	x	x	Ice Dragon Cooling	MatterHackers	MS3MQJT1	1kg Spools	1	19.99	0	1	19.99
5	Jet Block	Blue MH Build Series ABS Filament - 1.75mm (1kg)	x	x	Ice Dragon Cooling	MatterHackers	MS3MQJT1	1kg Spools	1	19.99	0	1	19.99
6	Copper Cooling Block	Green Copper Cooling Block	x			Ice Dragon Cooling			1	0	0	0	0
7	Cylinder	Recycled Polytetrafluoroethylene (PTFE) Rod	x	x	USC ME Department	McMaster-Carr	8803K18	1ft Rods	1	21.68	\$35	1	\$57
8	Pistons	Steel rod	x	x	USC ME Department	Lowe's Home Improvement	71499	1/2 Inch x 3 ft rod	2	8.49	\$35	1	\$43
9	Assembly Screws	Socket Cap Screws	x			Ace Hardware	43873	M3-0.50 - M6-1.00	12	0.25	0	0	3
10	Sealant Screws	Sealing Flat Head Screws, M4 x 0.7 mm Thread Size	x			McMaster-Carr	98070A680	Pack of 10	4	7.43	0	0	7.43
11	Piston O-Rings	Square-Profile Oil-Resistant Buna-N O-Ring, 1/16 Fractional Width	x			McMaster-Carr	4061T117	Pack of 100	1	10.48	0	0	10.48
12	Springs	Stacked Wave Disc Spring for 3.5 mm Shaft Diameter	x			McMaster-Carr	1807N115	0.13 mm Thick, 5.52 mm High	2	7.96	0	0	15.92
13	3D Printer Bed Adhesion	Elmer's Washable School Glue Stick - Disappearing Purple	x			Office Depot	930105	0.77 oz stick	1	2.59	0	0	2.59
14	Epoxy	Gorilla 2 Part Epoxy, 5 Minute Set, .85 ounce Syringe, Clear	x			Ace Hardware	1590793	0.85 ounce syringe	1	6.99	0	0	6.99
15	Silicone	Ace Window and Door Silicone	x			Ace Hardware	1213214	2.8oz tube	1	4.59	0	0	4.59
16	Clear Vinyl Tubing	3/8 inch ID 1/2 inch OD	x			Lowe's Home Improvement	879263	10 ft cut	1	4.38	0	0	4.38
17	Silicone O-Rings	0.13 mm Thick, 5.52 mm High	x			McMaster-Carr	1283N427	Pack of 25	2	4.36	0	0	8.72
												Sum of Material	154.22
												Sum of Labor	\$70
												Subtotal	224.22
												Total with Contingencies	269.06

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